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A STUDY OF GROUNDWATER-SURFACE WATER INTERACTION IN THE WINTER RIVER, PRINCE EDWARD ISLAND USING SEEPAGE METERS AND MINI-PIEZOMETERS

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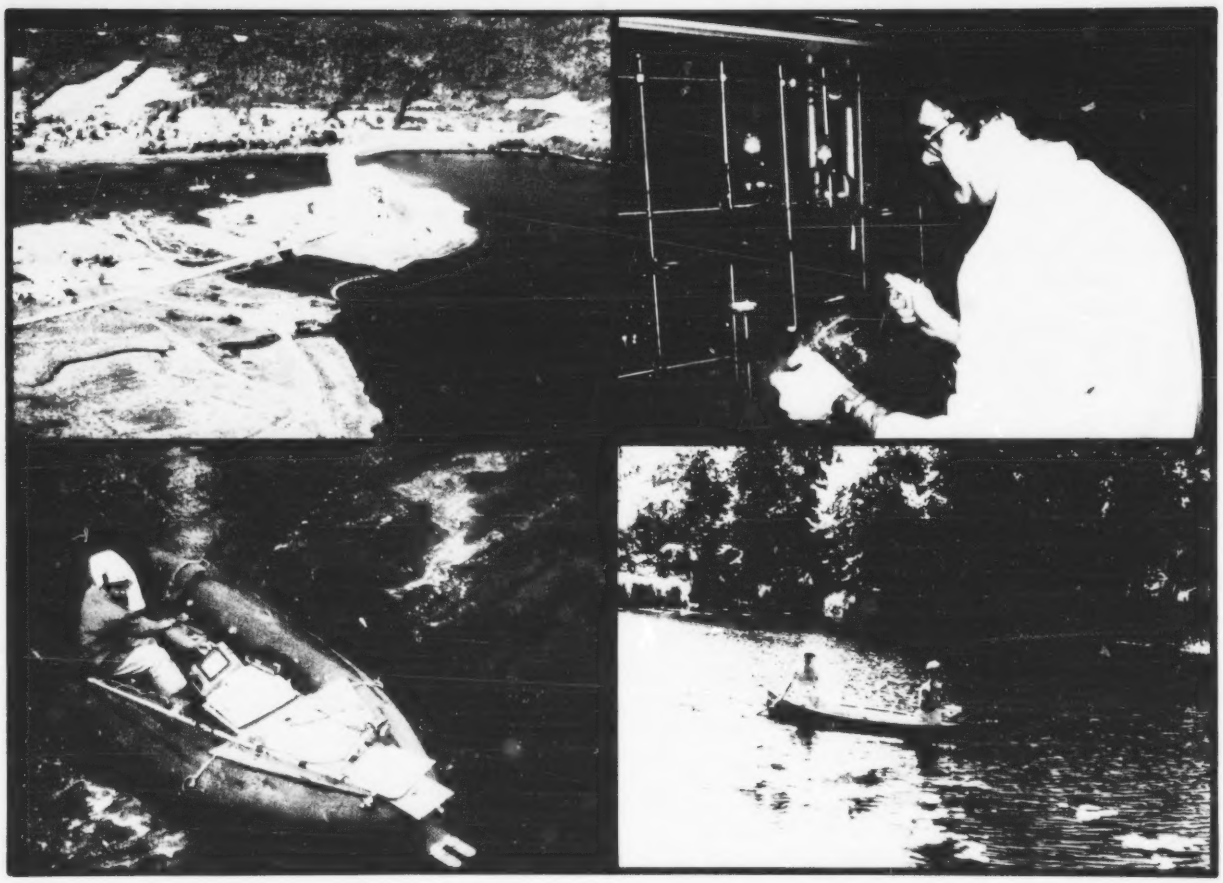

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A STUDY OF GROUNDWATER - SURFACE WATER INTERACTION IN THE WINTER RIVER, PRINCE EDWARD ISLAND USING SEEPAGE METERS AND MINI-PIEZOMETERS

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PREFACE

This study on surface water/groundwater interactions was part of the federal contribution to the pre-planning activities focussing on the Winter River Basin as a source of groundwater supply. The Federal-Provincial Water Management Program was undertaken in the Winter River Basin to describe the aquifer hydraulics of the system with respect to the major pumping centres that supply the City of Charlottetown and environs.

Over the last several years concern has been expressed regarding the reliability and sensitivity of the existing water supply for the Charlottetown area. This report, together with others, has helped define the dynamics of surface water/groundwater interactions that have to be considered in managing a river basin of this nature for water supply purposes. This information, together with other research projects, done jointly with Memorial University and the Province of Prince Edward Island will help in understanding the three dimensional aspects of the Basin, the variability in well yields, base flow to streams, recharge and the implications of surface activities to the integrity of the water quality of the Basin. All of these factors point to the need, and stress the importance, of jointly managing the surface and groundwater resources of a basin in harmony. This need is emphasized by the linkages of these two resources which are so interdependent and part of the same cycle.

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ABSTRACT

There is concern that municipal groundwater withdrawals from the Brackley and Union well fields in the Winter River basin, Prince Edward Island, may be diverting baseflow from the Winter River. Consequently, a field study, using seepage meters and mini-piezometers, was undertaken to measure zones of groundwater recharge and discharge through the bed of the Winter River from Brackley to Suffolk - a distance of nearly 17 kms. Also examined was the groundwater-surface water interaction occurring under the experimental conditions of excessive pumping and non-pumping in the Brackley and Union well fields. A field test of precipitation versus seepage flux response indicated no significant correlation with a small rainfall event.

Direct measurements of seepage flux were obtained from 29 sites at 8 locations, and falling head tests were conducted at 52 sites in 9 locations. Spatial differences in seepage flux ranged between zero and 8.9×10^{-4} cm/s. Values of K_h ranged between 6.7×10^{-6} cm/s and 2.9×10^{-3} cm/s, with an average K_h of 5.9×10^{-4} cm/s. Values of K_V ranged between 3.8×10^{-5} cm/s and 2.0×10^{-2} cm/s, with an average K_V of 2.8×10^{-3} cm/s.

The study area is primarily a discharge zone under natural conditions and a recharge zone near the Brackley and Union well fields. Although groundwater continued to move upward through the upper 20 cm of streambed during the pumping experiment, a portion of the groundwater supplying the Brackley and Union wells appears to be captured underflow and water induced directly into the aquifer from river flow.

RÉSUMÉ

Plusieurs sont inquiets du fait que les extractions municipales d'eau souterraine à partir des réseaux de puits à Brackley et à Union dans le bassin versant de la rivière Winter à l'Ile-du-Prince-Edouard pourraient enlever à l'écoulement de base de cette même rivière. Donc, une étude sur le terrain a été entreprise afin de jauger, à l'aide d'un indicateur d'infiltration et d'un mini-piézomètre, les zones de recharge et de décharge de l'eau souterraine à travers le lit de la rivière Winter entre Brackley et Suffolk - une distance de presque 17 km. On a aussi examiné l'interaction entre les composantes d'eau souterraine et d'eau de surface lors d'expériences de sur-pompage et d'arrêt de pompage dans ces mêmes réseaux de puits. Un test sur terrain entre la précipitation et la réaction du flux d'infiltration n'indiqua aucune correlation significative avec une petite averse de pluie.

Des indications du flux d'infiltration furent obtenues à 29 points provenants de 8 différents sites et des tests de perte de charge furent effectués à 52 points à 9 différents sites. La variation spatiale du flux d'infiltration se situait entre zéro et $8,9 \times 10^{-4}$ cm/s. La valeur du K_h variait de $6,7 \times 10^{-6}$ cm/s à $2,9 \times 10^{-3}$ cm/s, et en moyenne se situait à $5,9 \times 10^{-4}$ cm/s. Pour sa part, le Kv variait de $3,8 \times 10^{-5}$ cm/s à $2,0 \times 10^{-2}$ cm/s avec une valeur moyenne de $2,8 \times 10^{-3}$ cm/s.

La région étudiée en est une de décharge en temps normal et une de recharge près des réseaux de puits à Brackley et à Union. Malgré une montée continuelle de l'eau souterraine à travers les 20 cm supérieurs du lit de la rivière durant l'expérience de pompage, il apparait qu'une partie de l'eau souterraine approvisionnant les puits de Brackley et de Union soit captée à partir du ruissellement souterrain et de l'écoulement de rivière entraîné dans l'aquifère.

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TABLE OF CONTENTS

		PAGE
	PREFACE	i
	ABSTRACT	ii
	RÉSUMÉ	iii
	ACKNOWLEDGEMENT	iv
	TABLE OF CONTENTS	v
	LIST OF FIGURES	vii
	LIST OF APPENDIX FIGURES	viii
	LIST OF TABLES	viii
1.	PURPOSE	1
2.	INTRODUCTION	1
3.	PREVIOUS WORK	1
4.	PHYSIOGRAPHY AND DRAINAGE	3
5.	HYDROGEOLOGICAL SETTING	4
6.	METHODOLOGY	6
	6.1 Overview	6
	6.2 Mini-piezometers	6
	6.3 Seepage Meters	8
	6.4 Stream Sediment Sampling	9
	6.5 Falling Head Tests	9
	6.6 Well Field Pumping Effects	10
7.	HYDRAULIC CONDUCTIVITY TESTS, PRESENTATION OF RESULTS	11
	7.1 Statistical Analysis of Hydrogeological Parameters	11
	7.2 Horizontal Hydraulic Conductivity	13
	7.3 Anomalous Results	14
	(a) Brackley Pond	14
	(b) Union Station Site No. 1,2,3, and 4.	14
	(c) Officers' Pond	16
	7.4 Vertical Hydraulic Conductivity	16
	7.5 Anisotropy	17
8.	COMPARISONS OF SPECIFIC DISCHARGE WITH THE HYDROGEOLOGICAL PARAMETERS OF K_h, K_v, AND I	19
9.	RESPONSE OF SEEPAGE FLUX TO RAINFALL	22

TABLE OF CONTENTS (Cont'd)

		PAGE
10.	RESULTS OF WELL FIELD PUMPING EXPERIMENTS	23
11.	CONCLUSIONS	27
12.	REFERENCES	29
	APPENDIX A - DESCRIPTIVE SUMMARIES AND LOCATION MAPS OF FIELD LOCATIONS AND TEST SITES IN THE WINTER RIVER	1
	Brackley Stream	2
	Brackley Pond	2
	Union Bridge	2
	Union Station	2
	Hardy's Pond	4
	York Stream	4
	York Pond	4
	Officers' Pond	7
	Suffolk	7

LIST OF FIGURES

FIGURE NO.		PAGE
1	Location Map of Winter River Basin, P.E.I.	2
2	Surficial Geology of Winter River Basin, P.E.I.	5
3	Location Map of Instrumented Sites, Winter River, P.E.I.	7
4A	Installation of Mini-Piezometer (Schematic)	8
4B	General Features of Seepage Meter (Schematic)	8
5	Range of Values - Horizontal and Vertical Hydraulic Conductivities	12
6	Graph of K_h versus K_v, Winter River, Prince Edward Island	19
7	Specific Discharge versus Mean Horizontal Hydraulic Conductivity	21
8	Specific Discharge versus Mean Vertical Hydraulic Conductivity	21
9	Schematic Cross-Sectional View of Potential Field and Flow Lines at Officers' Pond in the Winter River	22
10	Average Specific Discharges, Winter River, Prince Edward Island.	24
11	Brackley Well Field - Variations in Seepage Flux Due to Pumping Rates; Brackley Pond Sites 1 and 2.	25
12	Union Well Field - Variations in Seepage Flux Due to Pumping Rates; Union Bridge Site 2a and Union Station Site 2a.	25

LIST OF APPENDIX FIGURES

APPENDIX FIGURE NO.		PAGE
A-1	Locations of Instrumented Sites at Brackley Stream and Brackley Pond	2
A-2	Locations of Instrumented Sites at Union Bridge Bridge and Union Station	3
A-3	Locations of Instrumented Sites at Hardy's Pond	5
A-4	Locations of Instrumented Sites at York Stream and York Pond	6
A-5	Locations of Instrumented Sites at Officers' Pond	7
A-6	Locations of Instrumented Sites at Suffolk	8

LIST OF TABLES

TABLE NO.		PAGE
1.	Description of Stream Sediments	10
2.	Summary of Horizontal Hydraulic Conductivity Values - Winter River, P.E.I.	13
3.	Summary of Field K_h Measurements at Union Station	15
4.	Summary of Vertical Hydraulic Conductivity Values - Winter River, P.E.I.	17
5.	Summary Data and Values of Anisotropy - Winter River, P.E.I.	18
6.	Correlation of K_h, K_v and I with Specific Discharge	20
7.	Response of Seepage Flux to Rainfall	23
8.	Mini-Piezometer Data from the Well Field Pumping Experiment	26

1. PURPOSE

A field study was undertaken to define areas and rates of groundwater recharge and discharge through the bed of the Winter River. In addition, the response of groundwater discharge through the streambed to conditions of pumping and non-pumping of the wells in the Brackley and Union well fields was calculated.

2. INTRODUCTION

Water for the city of Charlottetown and portions of its surrounding municipalities is derived from the Brackley and Union well fields in the Winter River basin (Figure 1). Most of the basin also serves as the recharge area for the groundwater aquifer beneath it.

Current water use is about 5.7 billion litres annually. About 1.3 billion litres of annual water production capability was lost from the system when the Lower Malpeque well field, in the North Creek drainage basin, was taken out of regular use in 1983 due to water quality deterioration. This has placed increased stress on the Winter River well field. The Commissioners of Sewer and Water Supply (COSAWS)for the City of Charlottetown have stated that demands for water services have grown significantly in the past and are expected to continue increasing in the future. COSAWS (Henthorn, 1981) have also suggested that the greater Charlottetown area will be serviced by them by the turn of the century. Also, there is concern that the combined withdrawals of the numerous municipal wells, located near the Winter River, may have detrimental effects on the movement and availability of groundwater discharge to the river because of induced streambed infiltration. Prior knowledge of the directions of groundwater movement through the Winter River streambed and of its velocities would be useful to water managers in anticipating threats to the Charlottetown water supply, should an environmental mishap occur.

3. PREVIOUS WORK

Previous work comprised that which was either conducted, work shared and cost shared by Inland Waters Directorate, Prince Edward Island Department of Community and Cultural Affairs, COSAWS, and Fracflow Consultants. It also includes published reports by outside authors or agencies that tested, or have used, mini-piezometers and seepage meters in their investigations.

In previous work by Israelson and Reeve (1944), they used seepage meter techniques to measure directly the rate of irrigation canal losses. Warnick (1951, 1957), first described the use of a hand-driven

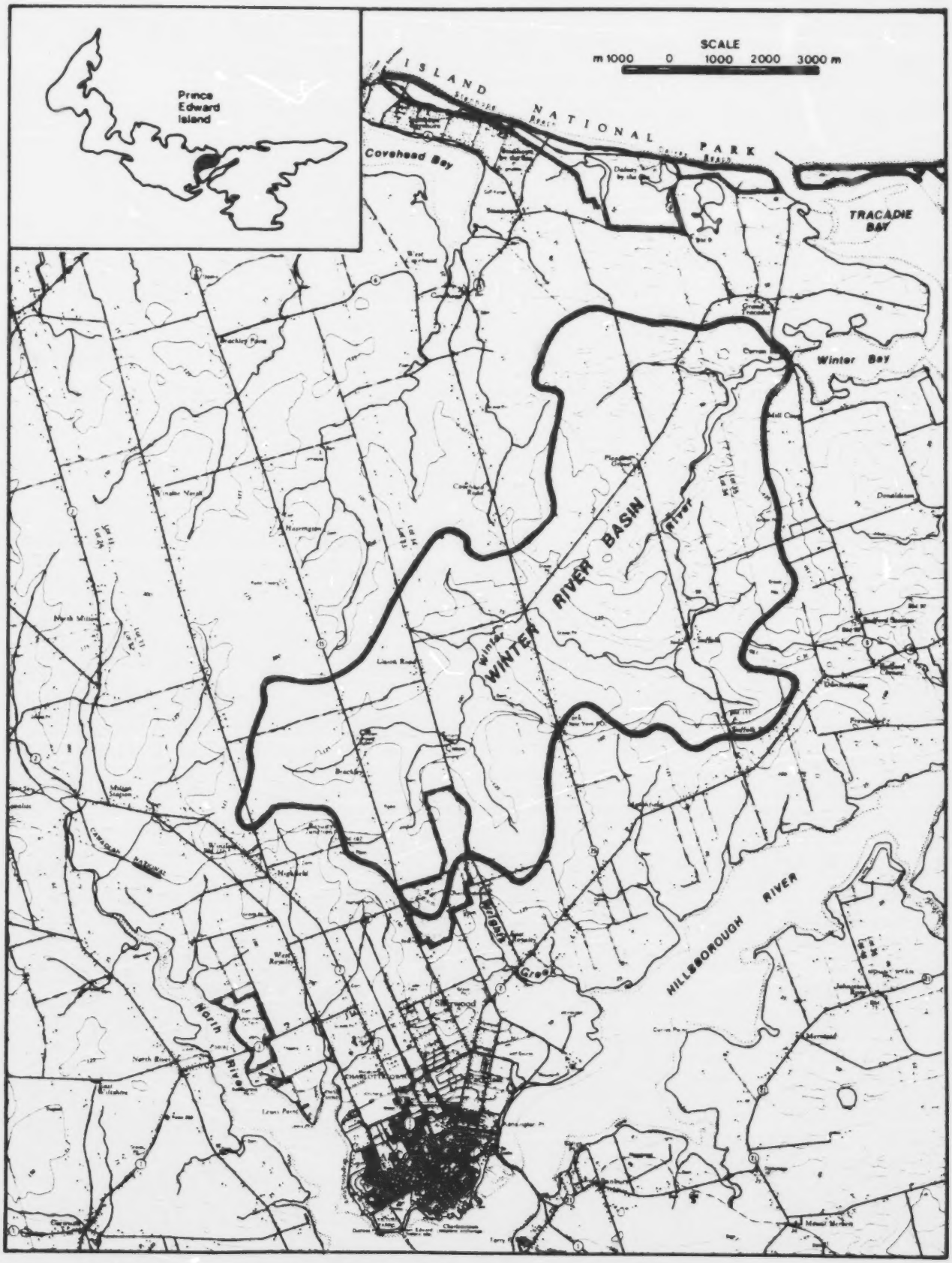


Figure 1 Location Map of Winter River Basin, Prince Edward Island.

piezometer to measure head differences between surface water and groundwater, using a seepage piezometer to measure irrigation canal seepage. Canal studies were also conducted by Ross et. al. (1964). The mini-piezometers used in this latter investigation were the type described by Lee and Cherry (1978) for use in groundwater/surface water studies. Prior to this, Lee (1972), employed a seepage meter technique at Lake Saille, Minnesota, by inserting the cut-off end of a steel drum (208 litre, 55 gallon U.S.) into the lake bed. A collection bag was installed on the drum to facilitate measurement of septic tank effluent.

Other studies that describe the usefulness and limitations of the seepage meter in quantifying groundwater/surface water interaction and discharged groundwater quality include: Pinder and Jones (1969), McBride and Pfannkuch (1975), Lee (1976, 1977), John and Lock (1977), Lee and Hynes (1978), Lee and Cherry (1978), Downing and Peterka (1978), Erickson (1979), Lee et. al. (1980), Fellows and Brezonik (1980), Price (1981), Woessner and Sullivan (1981), Belanger and Mikutel (1985) and Leibscher (1986).

4. PHYSIOGRAPHY AND DRAINAGE

Prince Edward Island is underlain by Permo-Carboniferous redbeds that generally tip to the northeast. The Island is physiographically separated into western, central and eastern divisions.

The Winter River basin is located in central Prince Edward Island, just north of the city of Charlottetown. Central Prince Edward Island is overlain by a north-westerly trending track of hills, with slopes in excess of 8^{o} and a topography of rolling farm land with elevations up to 120 metres above sea level (van der Poll, 1983).

The area north and northeast of Charlottetown is typically lowland, rising to 60 to 90 metres in a few localities. The Winter River basin has a length of about 13 kilometres, with maximum and average elevations of 67 and 30 metres respectively.

From its headwaters in the West Royalty-Sherwood-Winsloe area, the Winter River drains about 63 square kilometres of central Queens County and flows north-easterly to the Gulf of St. Lawrence via the Winter and Tracadie bays. The basin is drained by a relatively simple system of third order streams having a total length of about 51 kilometres. Winter River's main stem is about 21 kilometres long, with an average slope of 1.95 m/km. The lower 4.3 kilometres of the main stem, from Corran Ban Bridge to a location near Pleasant Grove are tidal. Along the main stem there are three principal dams: below Officers' Pond, Hardy's Pond and a shallow impoundment at the Brackley well field (Figure 1).

Drainage areas for selected locations within the basin include Winter River at the Brackley Stream gauging station, 4.92 km^2; Union

well field, 18 km^2; and Winter River at the Suffolk gauging station at Officers' Pond dam, 37.5 km^2. Stream discharge from the Brackley well field and from Officers' Pond dam is monitored jointly by the Water Resources Section of the Prince Edward Island Department of Community and Cultural Affairs and by the Inland Waters Directorate of Environment Canada.

5. HYDROGEOLOGICAL SETTING

The soft, Permo-Carboniferous redbeds underlying the Winter River basin are characterized by relatively rapid, lateral facies changes among sandstones, siltstones and claystones (Callan, 1978). The sites described by Callan are two kilometres away from the Union pumping station site described by Francis (1981). The boreholes drilled by Francis (1981) penetrated bedrock composed of 80% sandstone, with the remainder being clayey siltstone and claystone.

Structurally, the basin is underlain by a gently folded synclinal feature, the axis of which trends approximately east/west, passing through the Union well field. Bedding dips are generally less than five degrees (Francis, 1981). Glacial deposits thinly mantle the basin (0-10 metres) with, locally, clay-rich or sand-rich tills. Ablation tills occupy higher ground and glaciofluvial deposits lower elevations (Figure 2). More complete descriptions of the bedrock units and surficial deposits are given by Frankel and Crowl (1970), Prest (1973) and Van der Poll (1983).

The most significant criteria determining major hydrogeological units within the basin are the distribution of bedrock fracture patterns and, to a minor extent, the distribution of the glaciofluvial units (Callan, 1978). Outcrops are infrequent in the Winter River basin; however, described exposures have significant high-angled to vertical fracturing with local bedding plane separations (Callan, 1978). Studies of bedrock exposures along the south shore of Prince Edward Island have also shown that the main discontinuities in the bedrock are vertical to subvertical joint sets and horizontal bedding plane separations (Parsons, 1972). Vertical to steeply dipping joints, with inclinations greater than 75°, are widespread throughout the Island (Van der Poll, 1983). Francis (1981) reports that 82% of natural fractures in the sandstone aquifer at Union Station are horizontal bedding plane separations.

In both the Union and Brackley well fields, wells encounter significantly dense fracturing within a couple of metres of the bedrock surface (Callan, 1978). Francis (1981) showed that fracture frequency decreases with depth. Subvertical and total fracture frequency profiles suggest that the aquifer can be regarded as having two zones: an upper, highly fractured zone with significant subvertical fracturing, and a lower (below 35 metres), much less fractured zone with few subvertical fractures.

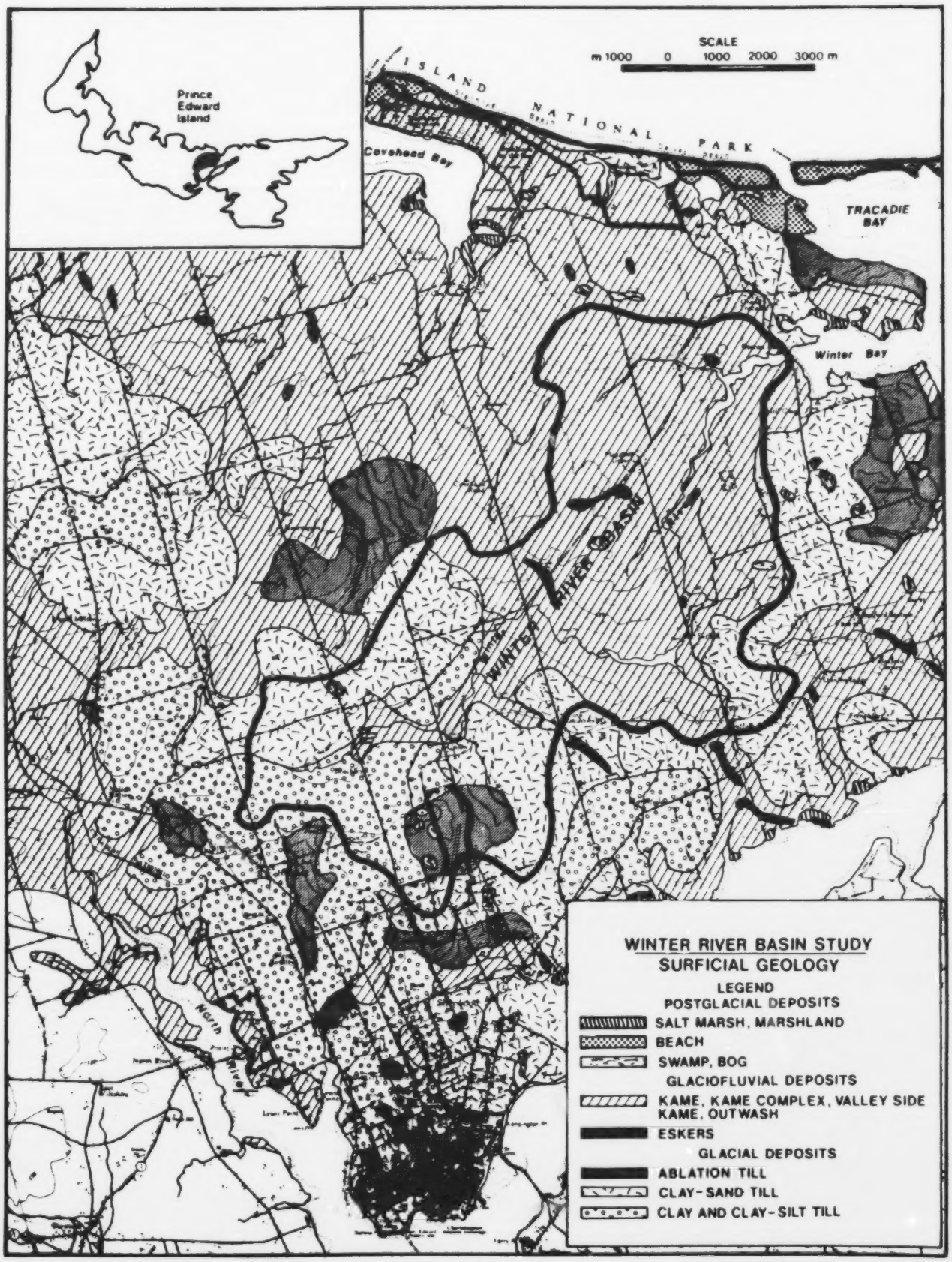


Figure 2 Surficial Geology of Winter River Basin, Prince Edward Island.

The significance of the glaciofluvial deposits lies in their capability to transmit recharge water and, perhaps, locally to provide storage. These deposits occur on topographically low positions and may, locally, represent aquifer potential in conjunction with fractured bedrock (Callan, 1978). However, relevant to this report are the sandy tills found on both flanks of the Winter River, and the clay-rich till which forms a wedge protruding into the Winter River basin from the southwest as far as the Union and Brackley well fields.

The highly permeable sand rich tills that overlie much of the basin and the high frequency of permeable fractures in the bedrock aquifer combine to allow easy access of surface pollution to the upper and most productive bedrock aquifer zones. Conversely, the clay rich till can act as a barrier between pollution on the surface and the shallow groundwater in the valuable bedrock aquifer.

6. METHODOLOGY

6.1 Overview

The installation and monitoring of seepage meters and mini-piezometers were conducted during the last week of June 1984 and continued until the last week of August 1984. Nine locations were chosen for instrumentation: Brackley Stream, Brackley Pond, Union Bridge, Union Station, Hardy's Pond, York Pond, York Stream, Officers' Pond and Suffolk (Figure 3). Brackley Stream was not instrumented with seepage meters due to a lack of streamflow. Although at the start of the project the river stage was high, the majority of observations were made during low flow conditions. Moreover, mean rainfall for July was 51.4 mm, 40 percent below normal.

Seepage meters and mini-piezometers were constructed in a manner similar to that described by Lee and Cherry (1978). The general features of construction and materials used are shown schematically in Figures 4a and 4b. A more detailed account is given in sections 6.2 and 6.3.

6.2 Mini - Piezometers

Mini-piezometers were installed in stream alluvium of various textures, varying from glacial till to sand and gravel, and occasionally into bedrock. A total of 37 mini-piezometers were installed either adjacent, or in close proximity to, one or more seepage meters. A lag bolt, 1.3 cm (1/2 in.) was loosely fitted to the bottom end of a 1.9 cm (3/4 in) ID, steel drive pipe to prevent its clogging with sediment. The drive pipe was manually driven to the desired depth below stream level. Installation of the drive pipe was problem free except where stream sediments were too shallow to ensure a firm footing for the piezometer tip. This situation was usually overcome by probing each site with a stake until a suitable depth of alluvium was found, or by driving into the soft bedrock. Translucent tygon tubing (0.64 cm ID) was perforated and wrapped with fibreglass cloth to prevent the piezometer tip from

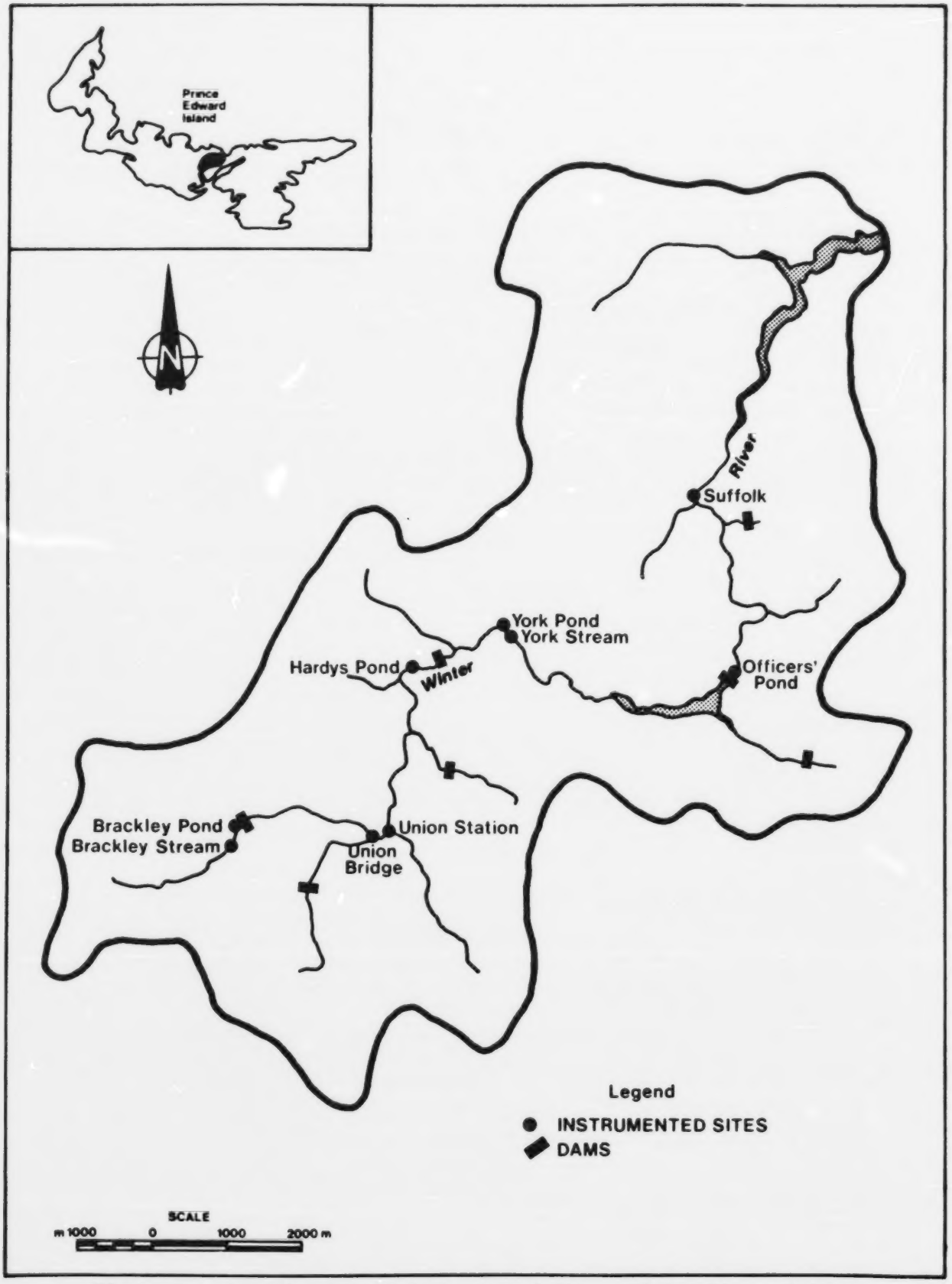


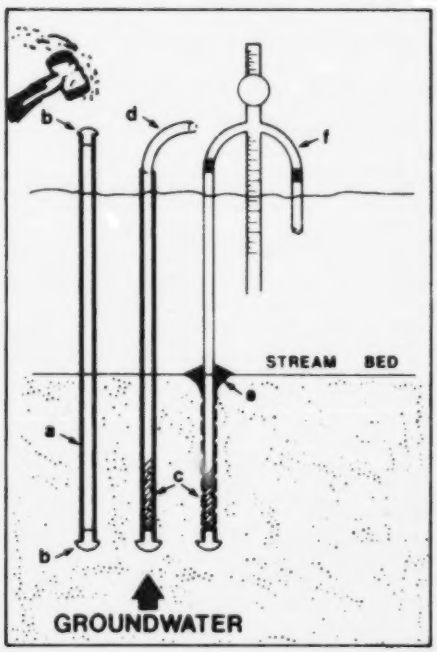
Figure 3 Location Map of Instrumented Sites, Winter River, Prince Edward Island.

clogging with sediment. A small amount of biodegradable dye (fluorescein sodium) was added to each piezometer tip to aid in measuring hydraulic heads. Semi-rigid, 0.31 cm (1/8 in.) ID polyethylene tubing was then inserted into the piezometer tip and lowered to the bottom of the drive casing. The piezometer tip was fitted snugly in place by gently working the drive casing during its removal from the hole. Upon removal of the drive casing bentonite pellets were used as a sealant to prevent leakage between the piezometer tube and the overlying water body. Each mini-piezometer was then taped to a stand pipe to facilitate easy measurement of hydraulic heads.

A manometer was used to measure accurately the hydraulic heads relative to the surface water level. A length of tygon tubing was attached to the top of the piezometer tube, suction applied and the free end lowered below the water surface. The manometer tube was then secured to a stake with a band of black electrical tape. The head difference between the stream or pond surface and the mini-piezometer was measured by comparing the water levels in each tube. Mini-piezometers were left in place once installed.

6.3 Seepage Meters

The end sections of steel drums (208 l., 45 Gal. Brit.) were used as seepage meters. A circular hole was cut into the top and the side walls of 12 drums. The seepage meters were operated by inserting a suitable sized rubber stopper, attached to a deflated two-litre plastic



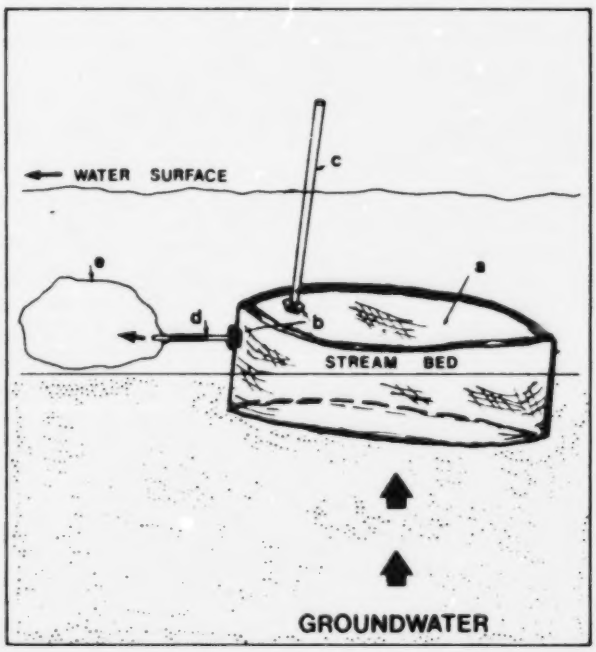


Figure 4A General Features of Mini-Piezometer. a - 1.9 cm (3/4 in.) ID steel drive pipe; b - 1.3 cm (1/2 in.) loosely fitted lag bolt; c - 0.64 cm (1/4 in.) ID translucent tygon tubing, perforated and wrapped with fiberglass cloth; d - semi-rigid 0.31 cm (1/8 in.) ID polyethylene tubing; e - bentonite seal; f - manometer.

Figure 4B General Features of Seepage Meter. a - end section of a steel drum (208 ; 45 Gal. Brit.); b - Circular holes with suitable size rubber stoppers; c - vent pipe semi-rigid 0.31 cm (1/8 in.) ID polyethylene tubing; d - rubber band wrap; e - 2 litre plastic bag.

bag, into the side wall orifice of the meter. Similarly, a vent tube with rubber stopper was inserted into the opening on the top of the meter. Collector bags were generally left on the meters for periods ranging from a few minutes (10-20) to a few hours (4 to 6). In some cases, however, collector bags were left on overnight. Collector bags that were found filled to capacity were not considered representative and were discarded because the actual filling rate was not known. Seepage volumes were measured with a graduated cylinder; and the time interval recorded and seepage flux determined by:

$$Q = \frac{v/t}{A}$$

where v in cm^3 is the volume of water entering the bag, t is elapsed time in seconds and A is the area surface covered by the drum in cm^2.

The installation of 34 seepage meters at eight river locations facilitated the measurement of seepage flux from 29 sites. Installations were effected by rotating the meters back and forth into the stream or pond bed to an average minimum depth of 15 to 20 centimetres. To reduce measurement errors due to possible gas build-up, the meters were positioned on an incline and fitted with vent pipes. Waders were worn when installing the instruments, thereby limiting data collection to water depths of less than 1 metre.

Initially, the seepage meters were located close to streambanks where wave action and the depth of water were minimal. The meters were moved away from streambank locations as river levels declined. Several measurements of seepage flux were obtained from each seepage meter emplacement before being removed to a new location.

6.4 Stream Sediment Sampling

Stream sediments along the Winter River were obtained by collecting 20 grab samples at instrumented sites. Textures ranged from silty clay to coarse sand and gravel. At many locations, significant amounts of cobble were encountered. Stream sections containing such materials were excluded from seepage meter observations due to the difficulty in placing seepage meters,and because of the potential for large errors in measurement. The results of stream sediment observations are summarized in Table 1.

6.5 Falling-Head Tests

Falling-head tests in the mini-piezometers were used to measure hydraulic conductivities in the sediments adjacent to mini- piezometer tips, and 52 tests were completed during the 1984 field season. At least one test was completed for each mini-piezometer and, in most cases, these were repeated. The falling head tests were analysed by the Hvorslev method (Case G, 1951) assuming semi-ellipsoidal, equipotential distribution about a horizontal plane at the midpoint of the piezometer screen. With the values so obtained, the calculated hydraulic conductivities were horizontal, (assuming the anistropy ratio of $K_h/K_v=1$).

In conducting the falling head tests, suction was applied to the open end of the piezometer tube to draw groundwater upward to the desired level (usually higher than 50 cm above static head). The open end of the piezometer tube was then pinched-off and taped, and the apparatus allowed to stabilize overnight before the water level was allowed to fall. An initial head measurement was taken. Next, falling-head levels were recorded at suitable time intervals, depending on the rate of fall, until they stabilized. Measurements were recorded until the falling-head disappeared below stream level in the cases where the static hydraulic head was below stream level.

TABLE 1

DESCRIPTIONS OF STREAM SEDIMENTS

Location	Site	Description and Comments
Brackley Stream	a	Silty sand
Brackley Pond	a	Black organics, fine to medium sandy silty clay occupies all measurement sites
Union Bridge	1a	Sandy Silt
	1b	(below bridge) Silty clay
	2a	Silty clay
Union Station	1a	Silty sand and gravel
	2a	Silty gravelly sand
	3a	Silty sand and gravel
	4a	Silty coarse sand
	1b	Silty pebbly sand
	2b	Silty gravelly sand
Hardy's Pond	a	Sand & gravel (all sites similar)
York Pond	1a & 1b	Sandy silt
York Stream	b	Medium sand; all sites similar
Suffolk	1	Fine to medium sand
	2c	Sandy, pebbly gravel
	3	Fine sand
Officers' Pond	a	Clayey sandy silt(all sites similar, loose and incoherent). Drive pipe ends in top few centimetres of fissile sandstone bedrock.

6.6 Well Field Pumping Effects

Experiments were conducted at the Brackley and Union well fields to determine if changes would occur in the magnitude and direction of seepage flux in response to changes in the rate of pumping.

Background measurements of seepage flux and piezometric levels were recorded periodically in the mini-piezometers and seepage meters at both well fields from August 20 until August 27. During this period pumping rates at the Brackley well field were kept at approximately 75 l/s. Pumping rates at the Union well field were more variable, ranging between zero and 85 l/s. The depth to water in the Brackley and Union well fields were also monitored.

Since both well fields are used to supply water to the City of Charlottetown, an alternating, off-on pumping cycle was employed (i.e. Union, off - Brackley, on; Brackley, off - Union, on) so that the monitoring programme could proceed without interruption to water service. The pumping rate at the Brackley well field was increased from approximately 70 l/s to about 138 l/s on August 27. A maximum pumping rate of 153 l/s was attained on August 28 at 0822 hours, when all available wells were pumping. All pumps were shut down for 24 hours at about 1400 hours on August 29. Variable pumping rates were subsequently recorded but none exceeded 40 l/s until about 1200 hours on August 31, when an average rate of 75 l/s was established.

Conversely, the Union pumping station was first turned-off around 1200 hours on August 27. A zero pumping rate was recorded until about 1500 hours on August 29, and the maximum pumping rate on that day was 131 l/s. Average pumping rates approaching 72 l/s were re-established at about 1030 hours on August 31. Mini-piezometer and seepage meter measurements were taken during pumping and non-pumping conditions at both well fields.

7. HYDRAULIC CONDUCTIVITY TESTS - PRESENTATION OF RESULTS

7.1 Statistical Analysis of Hydrogeological Parameters

The nature of hydraulic conductivity (K) can best be described in terms of heterogeneity and anisotropy (Freeze and Cherry, 1979). Summarized in Figure 5 are the study results of individual hydraulic conductivity values obtained from streambed sediments measured in the Winter River. A scale of hydraulic conductivity values is shown on the left side of the figure, and a representative range of geological materials (Modified after Freeze and Cherry, 1979) is given on the right side of the table. Station locations and site locations are presented along the bottom horizontal portion of the table.

The figure clearly shows variations in hydraulic conductivity values, in both space (heterogeneity) and in the direction of measurement (anisotropy). Geometric mean, hydraulic conductivity values were calculated from the measured values presented in Figure 5. The hydrogeological parameters of specific discharge (V) and hydraulic gradients (I) were computed from the field data and used in the statistical analysis. Specific discharge is an apparent velocity calculated from Darcy's law, which represents the flow rate at which water would move through an aquifer if the aquifer were an open conduit. The hydraulic gradients represent a change in total head with a change in distance in a given direction, and the direction is that which yields the maximum rate of decrease in head. Comparisons of the quantified parameters revealed significant information about the degree and nature of anisotropic-heterogeneity of unconsolidated sediments in the Winter River.

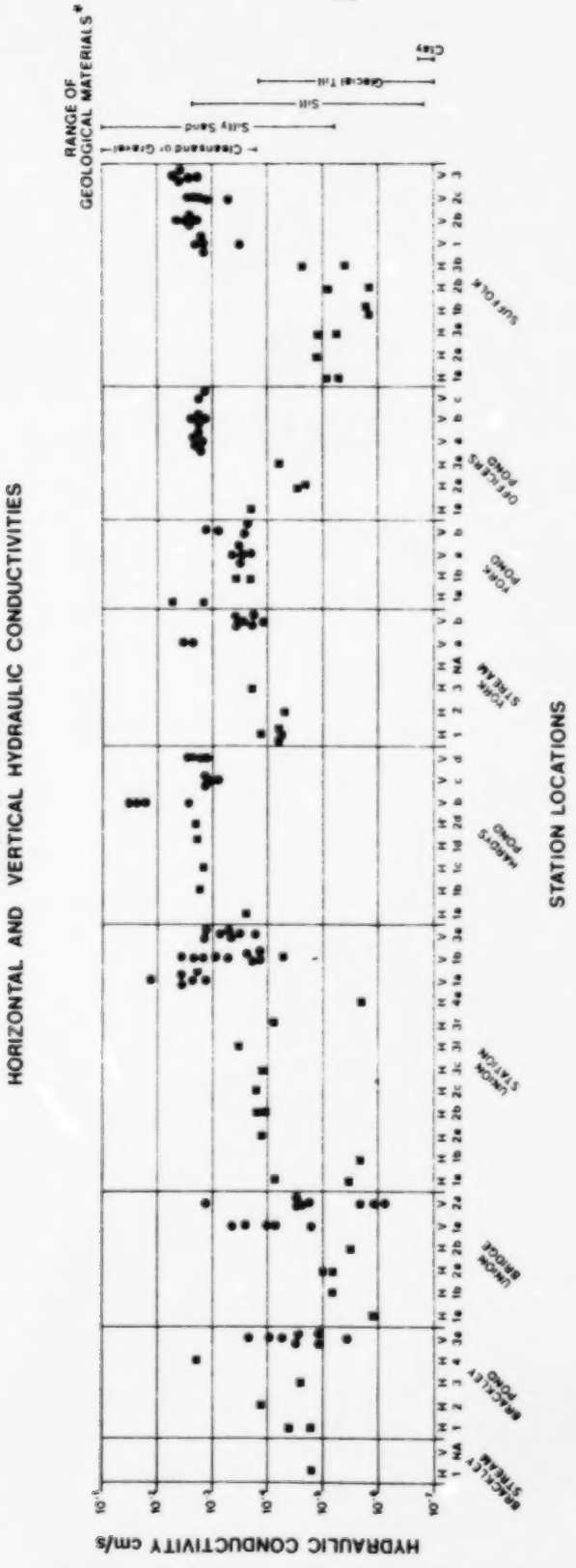


Figure 5 Range of Values - Horizontal and Vertical Hydraulic Conductivities.

7.2 Horizontal Hydraulic Conductivity

The results of horizontal hydraulic conductivity (K_h) measurements in the Winter River are summarized in Table 2. Because almost all of the values of K_h show relatively low standard deviations (On-1) and subsequent low coefficients of variation ($C.V._K$), most of the sediments studied can, therefore, be considered relatively uniform with respect to K_h at the location of measurement.

TABLE 2

SUMMARY OF HORIZONTAL HYDRAULIC CONDUCTIVITY VALUES WINTER RIVER, PRINCE EDWARD ISLAND

Locations	No. of Tests	$\bar{K}_h$ cm/s	On-1	$C.V._K$
Brackley Stream	1	2.5×10^{-5}	---	---
Brackley Pond	4	6.1×10^{-5}	3.5×10^{-5}	0.57
Union Bridge	5	6.7×10^{-6}	3.2×10^{-6}	0.47
Union Station	11	1.3×10^{-4}	1.3×10^{-4}	1.04
Hardy's Pond	5	1.9×10^{-3}	9.5×10^{-4}	0.50
York Stream	6	1.3×10^{-4}	7.6×10^{-5}	0.58
York Pond	4	2.9×10^{-3}	2.6×10^{-3}	0.90
Suffolk	11	1.0×10^{-5}	7.7×10^{-6}	0.77
Officers' Pond	4	1.3×10^{-4}	1.5×10^{-4}	1.15
ΣK_h	9	5.9×10^{-4}	1.1×10^{-3}	1.8

The K_h values of unconsolidated sediments in the Winter River study area ranged between 6.7×10^{-6} cm/s and 2.9×10^{-3} cm/s, with an average hydraulic conductivity of 5.9×10^{-4} cm/s (i.e. the sum of the geometric mean, hydraulic conductivities presented in Table 2). Groundwater circulation with respect to K_h is therefore most rapid in York Pond, and least rapid at Union Bridge.

The data also indicate that changes in the values of mean K_h generally occur randomly between measurement locations. Since the hydraulic density function is multimodal, and random in occurrence, the stream alluvium in the Winter River, therefore, displays discontinuous heterogeneity with respect to horizontal K between measurement locations.

Moreover, the coefficient of variation of 1.8, calculated from the K_h values presented in Table 2, quantifies the degree to which discontiniuous heterogeneity is reflected by K_h within the study area.

7.3 Anomalous Results

(a) Brackley Pond

An anomalous K_h value of 2.7×10^{-3} cm/s was derived for mini-piezometer No. 4 at Brackley Pond. The value was about two orders of magnitude higher than the other four K_h measurements taken at Brackley Pond. The $C.V._K$ with all five K_h measurements included would be 2.0, and without the single anomalous value, 0.57; and it is the latter value that is reported in Table 2. Leakage around mini-piezometer No. 4 may have introduced measurement error, and account for the higher than expected K_h value in this instance.

(b) Union Station

Union Station had a relatively high $C.V._K$ of 1.04 A closer review of the data indicated that the uniformity of sediments was site specific with respect to this location. Union Station was the longest stream section (about 250 metres) to be instrumented with mini-piezometers and seepage meters (Figure 2, Appendix A). This would tend to contribute to the elevated $C.V._K$ observed at Union Station. The station was divided into four measurement sites, numbered 1,2,3, and 4.

The results of K_h measurements at Union Station are presented in Table 3. Eight of the eleven K_h measurements from Union Station were measured from mini-piezometers at sites numbered 2, 3 and 4. A statistical analysis of these eight values yielded a mean K_h of 1.7×10^{-4} cm/s and a standard deviation of 1.4×10^{-4} cm/s. The representative $C.V._K$ for the above was 0.82. Site No. 1 values were not included in calculation of K_h because they would have introduced unreliable measurement values. The average sum K_h of the three measurements from mini-piezometers 1a and 1b was 3×10^{-5} cm/s. The standard deviation and $C.V._K$ were 4.5×10^{-5} cm/s and 1.5, respectively. The mini-piezometer data for sites 1,2,3 and 4 are further detailed below.

Site No. 1

The K_h of the three measured values from mini-piezometers 1a and 1b at Union Station site No. 1 was 1.3×10^{-5} cm/s, and the standard deviation was an elevated 4.5×10^{-5}cm/s. A $C.V._K$ was calculated from these values (1.50) and from the two values obtained from mini-piezometer 1a (1.2). The values of K_h therefore vary between the mini-piezometers at site No. 1 and between the two values obtained from mini-piezometer 1a.

The field-measured values of K_h at Union Station site No. 1, although suspect, are not considered to be disproportionate with the expected K_h value for this site. A high standard deviation between two measured values from one mini-piezometer may reflect measurement error in this case from possible clogging of the mini-piezometer screen. Leakage around the mini-piezometer is ruled out as source of error because K_h

TABLE 3

SUMMARY OF FIELD K_h MEASUREMENTS AT UNION STATION

(cm/s)

Site No.	K_h	$\bar{K}_h$	σ_{n-1}	C.V.$_h$
1	8.2×20^{-5} 5.2×10^{-6} 2.4×10^{-6}	3×10^{-5}	4.5×10^{-5}	1.5
2	1.5×10^{-4} 1.8×10^{-4} 1.7×10^{-4} 1.9×10^{-4}	1.7×10^{-4}	1.7×10^{-5}	0.2
3	1.1×10^{-4} 8.8×10^{-5} 4.8×10^{-4}	2.3×10^{-4}	2.2×10^{-4}	0.96
4	3.1×10^{-6}	-	-	-
2, 3, 4	-	1.7×10^{-4}	1.4×10^{-4}	0.82

values would likely rise rather than lower under leakage conditions. Note, however, that the standard deviation varied from the mean K_h value by a factor of 35, well within the range of internal heterogeneity of 1 or 2 orders of magnitude, which is not unusual for most geological formations (Freeze and Cherry, 1979). Several more mini- piezometers and measurements of K_h would be required to address the nature of K_h at Union Station site No. 1.

Site No. 2

The measurements from tests of hydraulic conductivity at Union Station site No. 2 appear reliable. A mean K_h value of 1.7×10^{-4} cm/s was determined from four field measurements, the low C.V.$_K$ of 0.10 indicates that sediments at site No. 2 were relatively uniform with respect to K_h.

Site No. 3

Measurements of hydraulic conductivity were obtained from the three mini-piezomters at Union Station site No. 3. The mean K_h value of 2.3×10^{-4} cm/s and the relatively low C.V.$_K$ (.96) apparently show that the sediments at site No. 3 are relatively uniform with respect to K_h, although less uniform than the sediments at Union Station site No. 2,

Site No. 4

A single K_h value of 3.1×10^{-6} cm/s was determined from mini-piezometer 4a in Union Station. The value, as reported, is probably a fair estimation of the K_h value but is likely to rise if several more field-measured values of K_h were available.

(c) Officers' Pond

The coefficient of variation of K_h from four measurements conducted on mini-piezometers 1a, 2a and 3a at Officers' Pond (Figure A6, Appendix A) was 1.15. Values of K_h varied by about one order of magnitude, ranging between 3.2×10^{-5} cm/s and 3.5×10^{-4} cm/s. The two K_h measurements from mini-piezometer 2a varied by less than two factors, to yield a mean K_h value of 3.8×10^{-5} cm/s. The stream sediments at the Officers' Pond location are therefore considered to be relatively uniform with respect to K_h.

7.4 Vertical Hydraulic Conductivity

The results of vertical hydraulic conductivity (K_v) measurements in the Winter River are summarized in Table 4. Measured values of K_v show overall, low standard deviations and subsequent low coefficients of variation($C.V._K$). This indicates that most stream sediments in the study area are relatively uniform with respect to K_v, in the vertical flow direction at the location of measurement, while discontinuous heterogeneity is apparent between measurement locations. This same conclusion was reached from the results of horizontal hydraulic conductivity testing.

Values of K_v for Winter River alluvium ranged between 3.8×10^{-5} and 2.0×10^{-2} cm/s, with an average vertical hydraulic conductivity of 2.8×10^{-3} cm/s. The lower K_v value of 1.9×10^{-5} cm/s was not included in the discussion due to its very high standard deviation of 3.51. The vertical movement of groundwater therefore appears to be least rapid at Brackley Pond, and most rapid at Hardy's Pond. The coefficient of variation value of 1.6, which was calculated from the K_v values presented in Table 4, quantifies the degree to which discontinuous heterogeneity is reflected by measured K_v values. However,three of the K_v values had $C.V._K$ above 1.00. These include the measured sites at Brackley Pond (3a), and Union Bridge (1a and 2a). The seepage flux data for these three sites showed highly irregular seepage flux patterns. Both the Brackley Pond and Union Station locations are areas where large groundwater withdrawals occur. The effect of large scale groundwater withdrawals on seepage rates appears to be site specific, as only three of twelve metered locations at Brackley and Union produced erratic seepage flux values. The influence of bedrock fractures probably accounts for the preferential disturbances to seepage flux patterns that were observed.

TABLE 4

SUMMARY OF VERTICAL HYDRAULIC CONDUCTIVITY (cm/s)
WINTER RIVER, PRINCE EDWARD ISLAND

Location	Seepage Meter	No. of Tests	$\bar{K}_v$	σ_{n-1}	C.V.$_K$
Brackley Pond	3A	8	3.8×10^{-5}	4.0×10^{-5}	1.07
Union Bridge	1A	6	1.3×10^{-4}	1.4×10^{-4}	1.09
	2A	8	1.9×10^{-5}	6.7×10^{-5}	3.51
Union Station	1A	6	3.6×10^{-3}	1.9×10^{-3}	0.52
	1B	10	5.9×10^{-4}	4.9×10^{-7}	0.001
	3A	7	6.8×10^{-4}	2.8×10^{-4}	0.42
Hardy's Pond	B	4	2.0×10^{-2}	1.6×10^{-2}	0.80
	C	4	1.6×10^{-4}	2.2×10^{-5}	0.14
	D	4	2.9×10^{-3}	5.2×10^{-4}	0.18
York Stream	A	2	1.9×10^{-4}	1.4×10^{-5}	0.07
	B	7	3.2×10^{-4}	1.1×10^{-4}	0.34
York Pond	A	5	4.3×10^{-4}	5.9×10^{-5}	0.14
	B	4	4.7×10^{-3}	6.5×10^{-4}	0.14
Suffolk	1a	5	1.4×10^{-3}	5.7×10^{-4}	0.41
	2B	5	7.6×10^{-3}	7.6×10^{-4}	0.18
	2C	5	1.8×10^{-3}	7.6×10^{-4}	0.43
	3	5	4.3×10^{-3}	7.3×10^{-4}	0.17
Officers' Pond	A	6	2.3×10^{-3}	1.2×10^{-4}	0.05
	B	4	2.7×10^{-3}	4.0×10^{-4}	0.15
	C	2	1.7×10^{-4}	2.1×10^{-5}	0.13
$\sum K_v$		20	2.8×10^{-3}	4.5×10^{-5}	1.6

7.5 Anisotropy

Hydraulic conductivity values at Hardy's Pond, York Stream, York Pond and Suffolk showed that the sediments were anisotropic at those locations. The locations correspond to sites where both the horizontal and vertical conductivity values produced coefficients of variation of

0.90 or less. A summary of the data used and the resulting values of anisotropy are presented in Table 5.

TABLE 5

SUMMARY DATA AND VALUES OF ANISOTROPY
WINTER RIVER, PRINCE EDWARD ISLAND

Location	Piezometer Sites	$\bar{K}_h$ cm/s	Seepage Meter Site(s)	$\bar{K}_v$ cm/s	K_h/K_v
Hardy's Pond	1a, 1b, 1c and 1d	1.9×10^{-3}	b	2.0×10^{-2}	0.1
			c	1.6×10^{-4}	12.0
			d	2.9×10^{-3}	0.7
York Stream	1, 2 and 3	1.3×10^{-4}	a	1.9×10^{-4}	0.68
York Pond	a and b	2.9×10^{-3}	a and b	4.5×10^{-4}	6.4
Suffolk	1a, 2a, 2b 3a and 3b	1×10^{-5}	1a, 2b, 2c and 3	3.8×10^{-3}	0.003

A scattergram of horizontal versus vertical conductivity is provided in Figure 6. Values falling below the line of equal hydraulic conductivity represent areas where horizontal K is greater than vertical K. Conversely, those points above the line are from areas where vertical K is greater than the horizontal K. Isotropic conductivities would be situated on the line, but no such values are reported. Note that 82% of the conductivity values lie above the line of equal K, thus showing anisotropies as being greater in the vertical direction.

A regression coefficient for the relation of mean horizontal hydraulic conductivity and mean vertical hydraulic conductivity produced a moderate correlation value of 0.47. The degree to which other possible parameters influence the relation of K_h and K_v is not known.

The anisotropic characteristics of the bedrock aquifer in the Winter River can influence anisotropy in the alluvium. Gale et. al. (1982) have reported that anisotropy can exist at three levels or scales in fractured porous aquifers. Anisotropies include the megascopic alternating sequence of sandstone and claystone (Van der Poll, 1981), preferred orientations of the fractures (Inland Waters Directorate, 1978); (Francis, 1981); Lajtai and Stringer, (1981); and rock mass anisotropy due to the preferential orientation of clay minerals that are typically parallel to the bedding planes. All three levels of anisotropy characteristically produce horizontal permeabilities that are generally much greater than the vertical permeabilities.

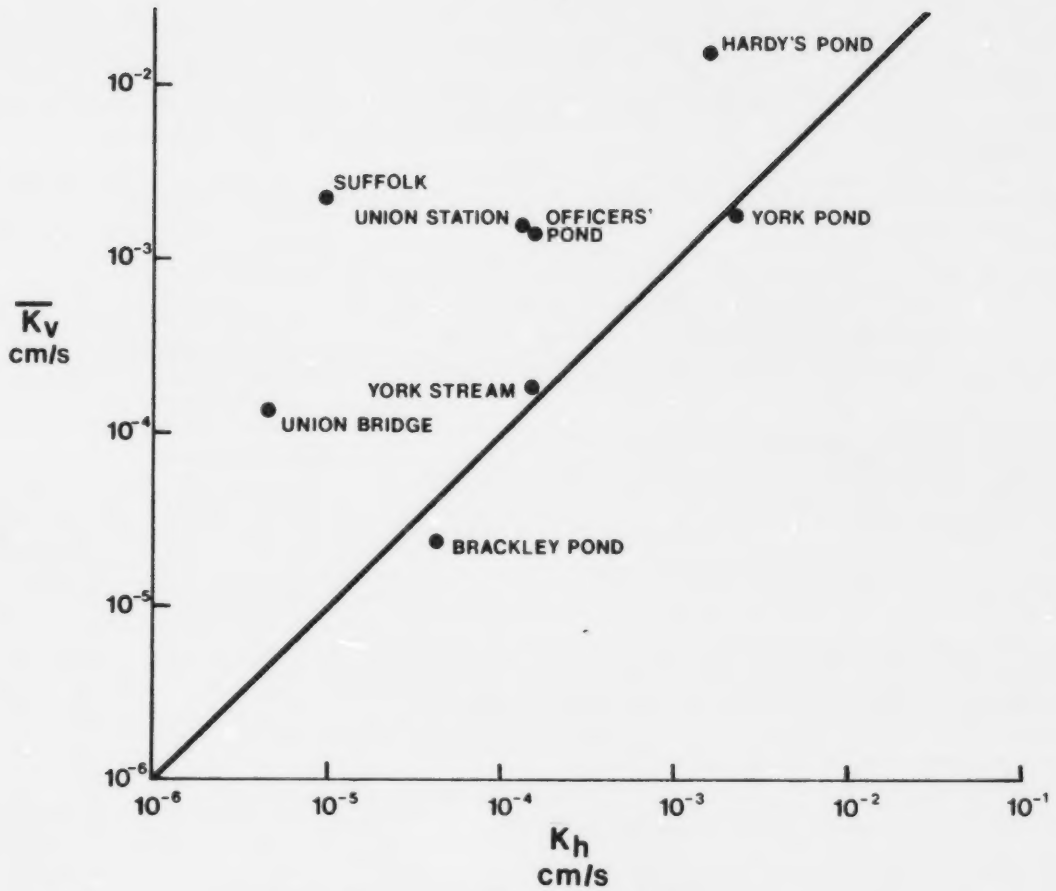


Figure 6 Graph of $\overline{K}_h$ versus $\overline{K}_v$, Winter River, Prince Edward Island.

The average total hydraulic conductivity of the upper 35 metres of the bedrock aquifer in the Winter River study area was measured at 10^{-2} cm/s (Gale et. al., 1982). Horizontal mean K in the overlying stream alluvium ranged between 10^{-3} to 10^{-6} cm/s, depending on the location of measurement. The lower bedrock aquifer, with its higher horizontal conductivity value, would be expected to act as a major conduit of flow. Flow in the lower conductivity stream sediments would generally be vertical. Increases in the difference between conductivity in the overlying stream sediments and in the bedrock will produce increases in the components of vertical flow, as more of the flow is carried in the lower unit. Differences between the hydraulic conductivities of the stream sediments and of the bedrock aquifer are therefore significant, because they help control the directional components of groundwater flow.

8. COMPARISONS OF SPECIFIC DISCHARGE WITH THE HYDROGEOLOGICAL PARAMETERS OF K_h, K_v and I

The SPSS computer package was used to perform correlation analysis among several hydrogeological parameters. Specific discharge

was correlated with the parameters of horizontal and vertical hydraulic conductivities (K_h and K_v) and hydraulic gradients (I). The resulting correlation coefficients are presented in Table 6.

TABLE 6

CORRELATION OF K_h, K_v, AND I WITH SPECIFIC DISCHARGE

Specific Discharge	K_h	K_v	I
Correlation Coefficient	0.50	0.80	0.07
Significance	0.02	0.00	0.77

The correlation coefficient of 0.50 between specific discharge and horizontal K indicates moderate correlation. A relationship between the two parameters exists but is not clearly definable. What is clear, though, is that horizontal hydraulic conductivity is not a factor strongly controlling the discharge in the Winter River study area. Figure 7 shows a weak relationship between specific discharge and increases in horizontal K.

Although a correlation coefficient of 0.80 was calculated for specific discharge and vertical hydraulic conductivity in the Winter River study area, there appears to be no linear relationship between these parameters. However, the trend towards an increasing V with an increasing K_V is obvious in Figure 8.

The correlation coefficient of 0.07 for specific discharges and hydraulic gradients is very weak, apparently reflecting a random set of data points. However, hydraulic gradients ranged by a factor of 11 (0.009 to 0.10). Thus the variations in seepage flux appear to be controlled more by hydraulic gradients than by streambed materials.

The K_v values generally obtained from calculations of grain size correspond well with the mean K_v values derived from field measured stream sediments in the Winter River. However, at some locations, particularly Officers' Pond, silty and clayey sediments displayed unusually high K values. Apparently, the influence of hydraulic gradients and bedrock fracture permeabilities locally increase the effective porosities of stream sediments. This would account for the K_v values that reflect the permeabilities normally associated with the underlying fractured bedrock of the Winter River basin.

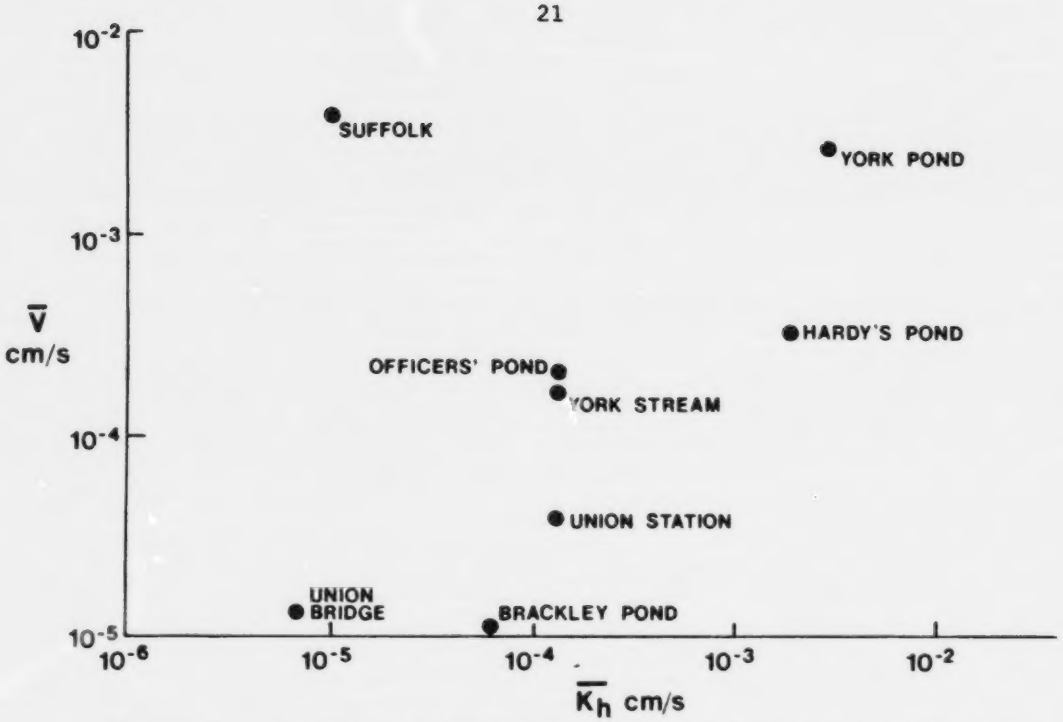


Figure 7 Specific Discharge versus Mean Horizontal Hydraulic Conductivity, Winter River, Prince Edward Island.

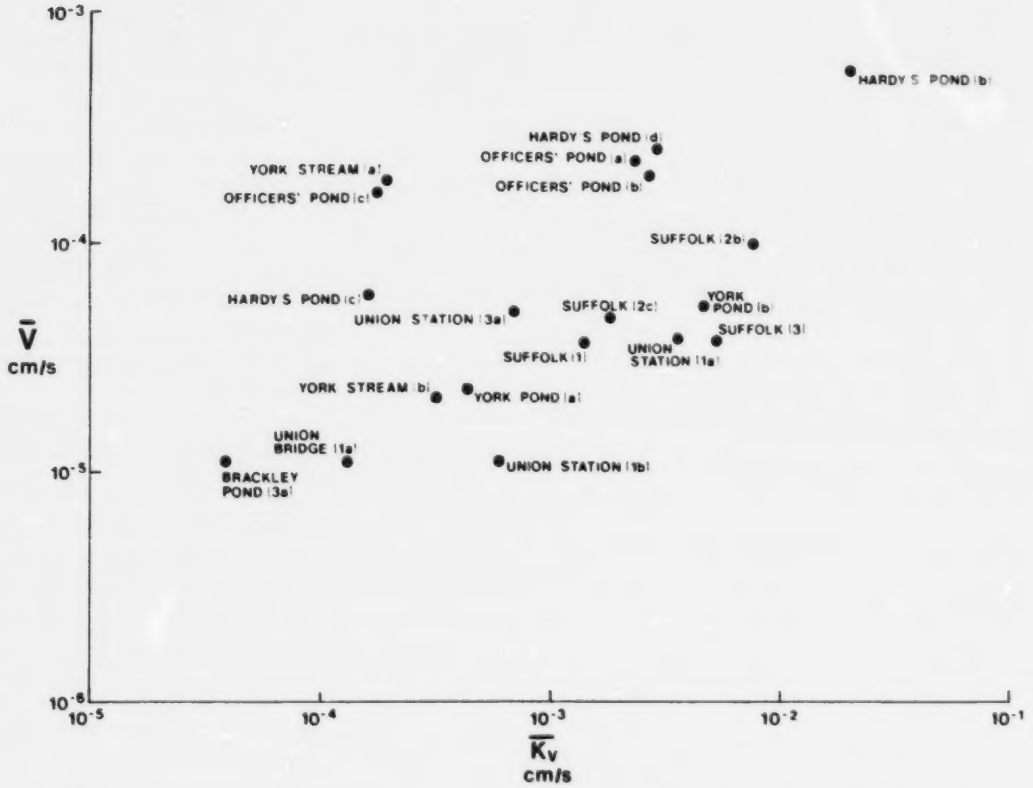


Figure 8 Specific Discharge versus Mean Vertical Hydraulic Conductivity, Winter River, Prince Edward Island.

Field-measured values of static head were used to construct a schematic profile of groundwater flow to the Winter River at Officers' Pond. Field data were generally insufficient for the purpose of constructing cross-sections of groundwater flow at monitored sites. However, Figure 9 is considered representative of groundwater movement through the bed of the Winter River in discharge areas where the effects of large scale groundwater withdrawal is not encountered.

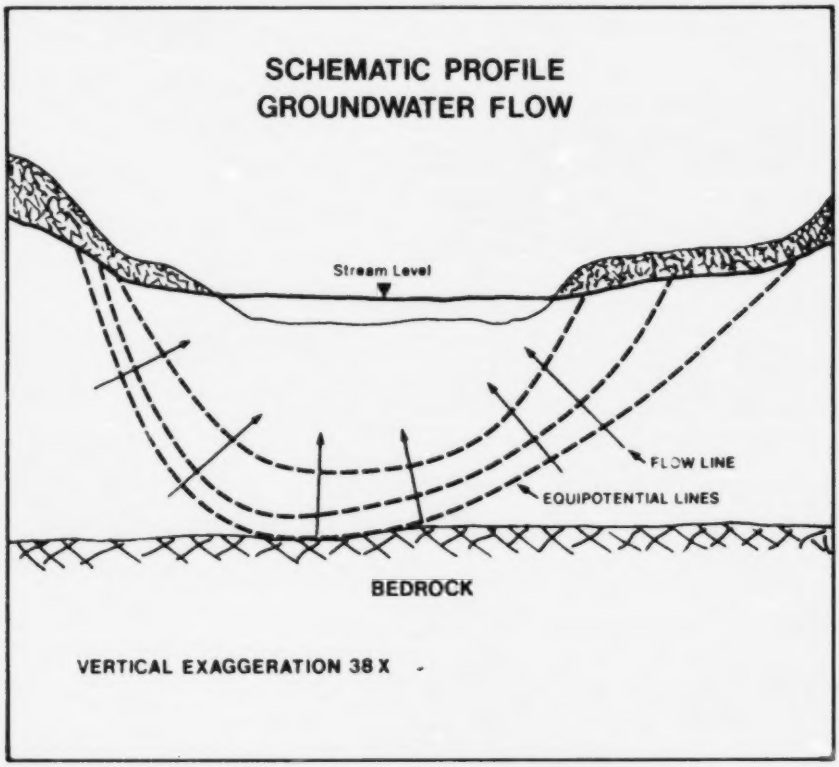


Figure 9 Schematic Cross-Sectional View of Potential Field and Flow Lines at Officers' Pond, Winter River, Prince Edward Island.

9. RESPONSE OF SEEPAGE FLUX TO RAINFALL

Records from the Atmospheric Environment Service (A.E.S.) of Environment Canada show total rainfall in July, 1984 to have been 51.4 mm, normal rainfall for July being 84.3 mm. The A.E.S. in Charlottetown recorded a 4.6 mm rainfall event on August 7, one day prior to monitoring the response of seepage flux to rainfall. On August 8, a small (3.2 mm) rain event was recorded.

Seepage flux was monitored at six locations: Brackley Pond (Site 2a), Union Bridge (Site 2b), Union Station (Site 2c), Hardy's Pond (Site d), York Pond (Site b), and Officers' Pond (Site c). The mean values for seepage flux from each of those specific sites are compared in Table 7. The findings show no major differences between the seepage flux measured during the field season and after the rainfall event. These results suggest that the magnitude of the rainfall event was generally too small to effect increases in seepage flux. However, Union Station site 2c may be worth noting because, even though the rainfall event was small, mean seepage flux prior to and after rainfall monitoring increased from 1.2×10^{-6} cm/s to 7.7×10^{-6} cm/s, respectively. Bedrock fracturing may have contributed to the increase in seepage flux observed at Union Station site 2c.

TABLE 7

RESPONSE OF SEEPAGE FLUX TO RAINFALL

Location	Site	Mean Seepage Flux cm/s		Number of Measurements	
		(A)	(B)	(A)	(B)
Brackley Pond	2a	3.4×10^{-7}	3.5×10^{-7}	3	1
Union Bridge	2b	3.6×10^{-5}	2.2×10^{-5}	5	2
Union Station	2c	1.2×10^{-6}	7.7×10^{-6}	4	3
Hardy's Pond	d	2.6×10^{-4}	2.5×10^{-4}	4	2
York Pond	b	5.2×10^{-5}	3.0×10^{-5}	4	2
Officers' Pond	c	1.65×10^{-4}	2.4×10^{-4}	2	2

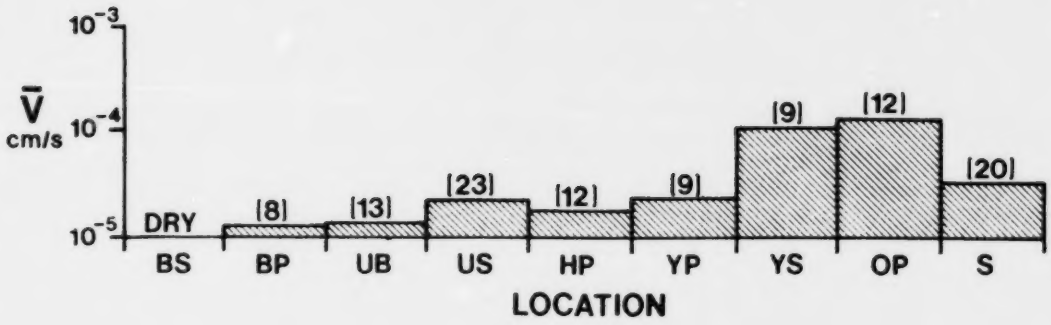
(A) Denotes seepage flux measurements made prior to August 8 rainfall event.

(B) Denotes seepage flux measurements made during August 8 rainfall event.

10. RESULTS OF WELL FIELD PUMPING EXPERIMENT

The well field pumping experiments were conducted after establishing the existence and extent of groundwater discharge through the sediments in the Winter River. Discharge velocities at Brackley and Union were noticeably less in comparison to most other locations in the study area (Figure 10) and piezometric heads were mostly below stream

level, indicating a downward component of flow: of greater significance, however, are the seepage flux and particularly the piezometric head data, collected during the well field pumping experiments.



[1] NUMBER OF MEASUREMENTS USED IN CALCULATIONS.

DRY BRACKLEY STREAM WAS DRY DURING THE STUDY.

Figure 10 Average Specific Discharges, Winter River, Prince Edward Island.

The magnitude of groundwater discharges, as measured in the seepage meters around the Brackley and Union well fields, were shown to be inversely related to well field pumping rates. In Figure 11 are two examples of Brackley Pond seepage fluxes responding to large variations in well field pumping rates. Clearly, groundwater seepage decreases with increases in the pumping rate, and vice versa.

Examples of the Union well field seepage flux response to variable pumping rates are presented in Figure 12. Union Station seepage flux variations tend to be about one order of magnitude larger than those for Union Bridge. This is likely due to the closer proximity of the Union Station seepage meter to the center of pumping.

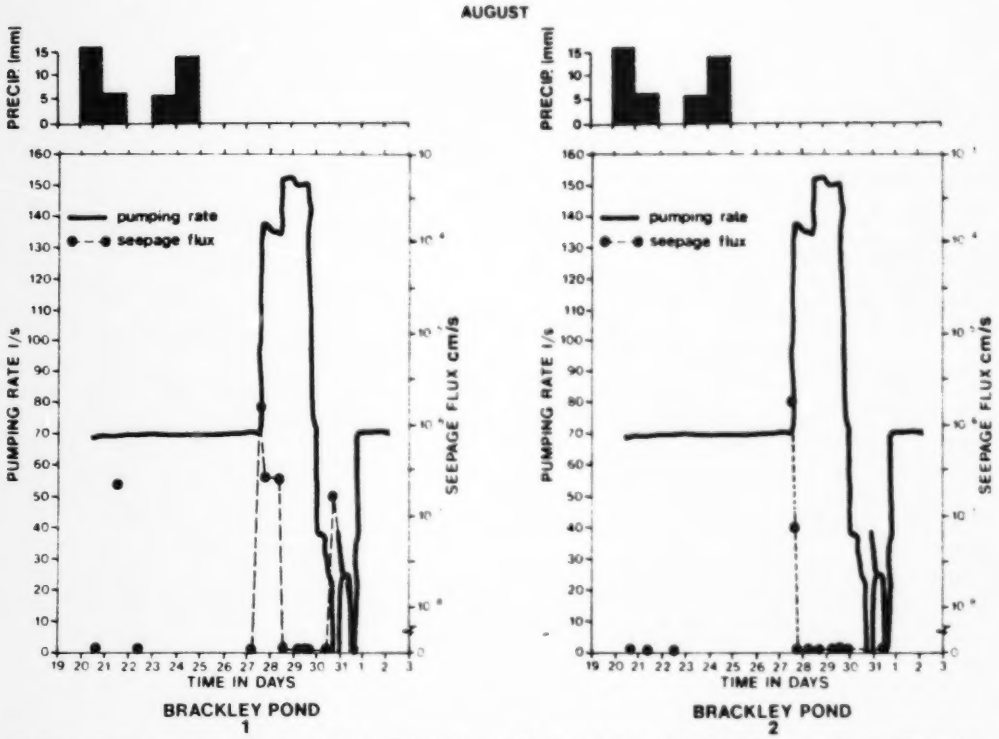


Figure 11 Brackley Well Field - Variations in Seepage Flux Due to Pumping Rates; Brackley Pond Sites 1 and 2.

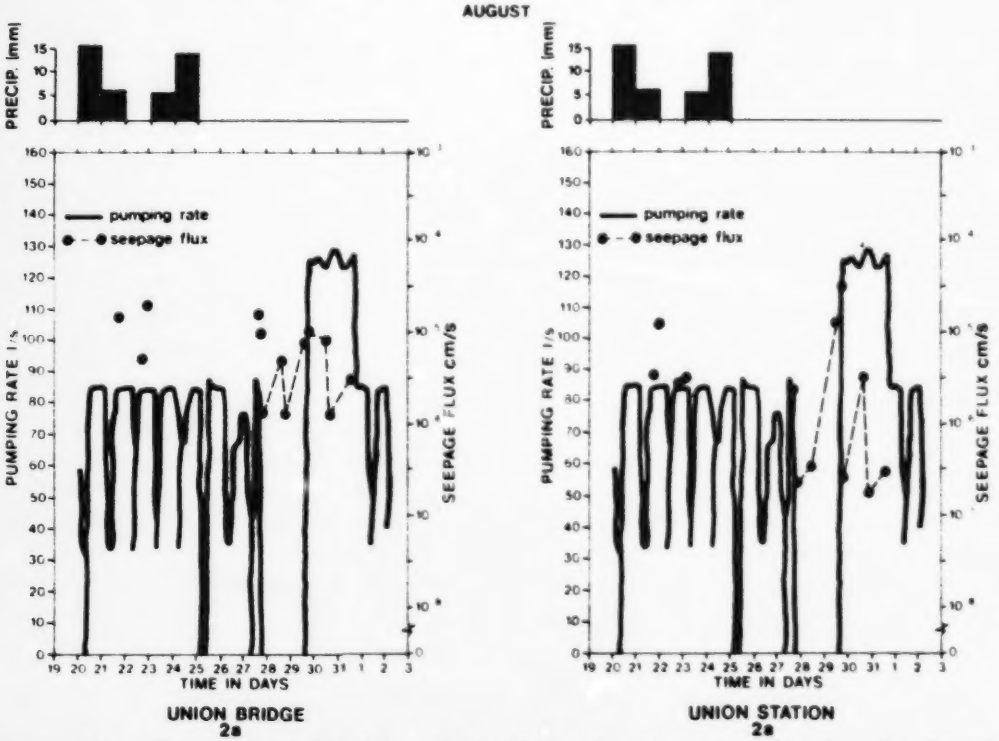


Figure 12 Union Well Field - Variations in Seepage Flux Due to Pumping Rates; Union Bridge Site 2a and Union Station Site 2a.

The data from Brackley and Union indicates that the flow system around the well fields are sensitive to changes in pumping rates, but that relatively large pumping variations are required to effect small changes in seepage fluxes.

Generally, the values of the hydraulic potentials in the mini-piezometers at Brackley and Union decrease downward, indicating downward seepage. The hydraulic head data, which was collected during the well field pumping experiments, is presented in Table 8. Pumping rates are shown to affect the rate and direction of seepage in the shallow flow field of both well fields. The degree to which the hydraulic heads in individual mini-piezometers are affected by pumping rates is a function of their distance from the center of pumping and depth. For example, the Brackley stream mini-piezometers appeared to be strongly influenced by well no. 9 (Figure 1, Appendix A) under both static and experimental pumping conditions, whereas the Brackley Pond site 4 mini-piezometer continued to show positive heads even though it is 7 centimeters deeper than the Brackley stream mini-piezometers. All four of the mini-piezometers in Brackley Pond lagged in their response to changes in pumping rates, which is likely a function of their distance from the center of pumping in well No. 1. Of significance in describing the depth-distance relationship to groundwater extraction rates are the data from Union Station mini-piezometers 2a, 2b and 2c. Mini-piezometer 2c, the shallowest one in this nest responded only slightly to variations in the pumping rate, whereas the two deeper mini-piezometers showed a strong shift to increasing upward seepage during the non-pumping cycle (-31 cm to +12.5 cm) and subsequently a strong decrease to -71.5 cm during the accelerated pumping cycle. Upward seepage will therefore likely occur within the upper 20 centimeters of the streambed under normal operating conditions.

TABLE 8

MINI PIEZOMETER DATA WELL FIELD PUMPING EXPERIMENT, WINTER RIVER, P.E.I.

BRACKLEY WELL FIELD

Location	Site	Piezometer Depth	Static Head	Hydraulic Head Pumps On	Hydraulic Head Pumps Off
Brackley Stream	1	108.	-27.	-52.38	29.5
	2	107.5	-23.8	-46.5	-35.5
Brackley Pond	1	108	- 0.75	- 1.63	- 1.5
	2	116.8	- 4.7	- 2.44	- 8.75
	3	101.6	- 2.98	- 7.18	- 8.13
	4	115.6	+ 0.4	+ 0.9	+ 0.75

UNION FIELD

Location	Site	Piezometer Depth	Static Head	Hydraulic Head Pumps Off	Hydraulic Head Pumps On
Union Bridge	1a	116.8	- 8.9	- 6.9	-15.75
	1b	86.4	- 9.6	- 9.17	N.A.
	2a	106.7	- 7.83	0.0	-10.38
	2b	30.5	- 1.17	- 0.8	- 1.63
Union Station	1a	121.9	- 6.13	- 3.75	- 8.25
	1b	134.6	7.25	- 2.75	- 3.1
	2a	127.	-34.6	+12.5	-29.75
	2b	119.4	-30.7	+12.5	-71.5
	2c	21.6	+ 0.83	- 0.83	- 9.13
	3c	24.1	- 1.7	+ 0.8	+ 0.4
	3l	132.1	-21.5	-11.3	-29.13
	4a	25.4	- 1.83	- 3.7	+ 3.6

Note: All Values in Centimetres.

11. CONCLUSIONS

1. Results from measuring positive heads in the mini-piezometers and seepage meters show that the bed of the Winter River is a discharge area, with discharging groundwater probably originating up-basin.

2. Small amounts of groundwater recharge in the upper few centimetres of the river bed occurred in the vicinity of Brackley Pond and Union Station, where negative hydraulic gradients predominated at depths below about 20 cm. This situation apparently is a function of recharge from local flow systems on the edge of the river.

3. Variations in seepage flux occurred at field locations where stream sediments were thought to be relatively uniform. However, the evolution of groundwater flow lines, particularly those associated with micro-discharge in complex local flow systems, is expected to vary. Differences in the local rates of groundwater flux can, for example, be caused when seepage meters are moved from one place to another in the same locale, also from small inputs to groundwater from precipitation and, likely, from river stage changes.

4. Vertical hydraulic conductivities were more variable at the Brackley Pond and Union Bridge locations than at all others that were monitored. This is probably a function of measurement frequency, about 70% of all K_v measurements were determined from the Brackley and Union locations.

5. Horizontal hydraulic conductivities were generally lower than vertical hydraulic conductivities at Union Bridge, York Stream, Suffolk and Officers' Pond. Also, more consistent measurements were usually attainable at the locations where water well pumping effects were not a factor.

6. The dry streambed and the significant downward hydraulic gradients experienced at the Brackley Stream location, strongly imply a correlation with groundwater withdrawals from the Brackley well field.

7. The values for specific discharge through the bed of the Winter River were lowest in the vicinity of the Brackley and Union well fields. A correlation with large groundwater withdrawals therefore exists. In addition, our experiments at the Brackley and Union well fields show that static head levels in mini-piezometers located in the bed of the Winter River respond rapidly to changes in well field pumping rates.

8. Increases in the rate of groundwater withdrawal decreases the potential for groundwater recharge to the Winter River in the vicinity of the Brackley and Union well fields.

9. There was no major change in the volume of seepage through the bed of the Winter River during the small rain event monitored. More detailed monitoring and a longer monitoring period after the cessation of at least one large rainfall event are required to evaluate properly this phenomenon.

10. The use of mini-piezometers as an inexpensive device for measuring static heads and horizontal hydraulic conductivities has proven effective. The mini-piezometer/seepage meter technique for measuring vertical hydraulic conductivities has proven to be inexpensive and useful, particularly in areas that are unaffected by groundwater withdrawals. However, the data from areas that are affected by large groundwater withdrawals can be extremely useful, provided a significant amount of data from numerous measurement points are available for interpretation.

11. Small but discernible specific discharge values were obtained from test sites in the Winter River. However, the higher seepage flux values that might be expected from groundwater discharge through cobble sized sediments are not easily monitored, nor are they expected to be accurate. This is mainly due to the difficulty with manually placing seepage meters in cobble graded streambeds, and the much reduced likelihood of securing an effective seal around the seepage meter because of the many large voids associated with these sediments.

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APPENDIX A

DESCRIPTIVE SUMMARIES AND LOCATION MAPS OF FIELD LOCATIONS AND TEST SITES IN THE WINTER RIVER

Brackley Stream

A single horizontal hydraulic conductivity (K_h) was measured at Brackley Stream mini-piezometer No. 2 (Figure A-1). The field value of K_h at a depth of 108 cm below the streambed was 2.5×10^{-5} cm/s. Streambed material was described as silty sand (Table 1). The streambed was dry at this location for most of the study period. Vertical hydraulic conductivity (K_v) measurements were not taken at Brackley Stream.

Brackley Pond

At the Brackley Pond location (Figure A-1), five horizontal and eight vertical hydraulic conductivity measurements were made in organic materials with the texture of sandy silty clay. Field values of K_h ranged between 3.4×10^{-5} and 2.7×10^{-3} cm/s. Horizontal measurements were conducted on the four available mini-piezometers, Nos. 1, 2, 3 and 4, at respective depths of approximately 108, 117, 102 and 116 centimetres. The two K_h measurements determined from mini-piezometer No. 1 varied by 19%. Measurements of vertical hydraulic conductivity were obtained from seepage meter 3a, and the hydraulic head data was determined by using mini-piezometer No. 3.

Union Bridge

Mini-piezometers 1a, 1b, 2c and 2d (Figure A-2) were used for falling head measurements. One horizontal hydraulic conductivity was determined from each mini-piezometer except 2c, from which two were derived. A total of 13 vertical hydraulic conductivities were also measured, five values were determined from seepage meter 1a and eight from seepage meter 2a.

Field values of K_h ranged from a low of 1.8×10^{-6} cm/s at site, 1a to a high of 8.5×10^{-6} cm/s at site 2a. A repeat measurement of K_h in mini-piezometer No. 1a varied by 7%.

Vertical hydraulic conductivities were measured at Union Bridge sites 1a and 2a. Seepage meters were set in sandy silt and silty clay, respectively. Vertical hydraulic conductivities ranged from 3.9×10^{-4} and 2.1×10^{-5} cm/s at Site 1a, and from 1.5×10^{-3} to 9.0×10^{-7} cm/s at Site 2a. Values of K_v varied by 96% in seepage meter 1a and by 229% in seepage meter 2a.

Union Station

Eleven horizontal and twenty-three vertical hydraulic conductivity measurements were made at Union Station (Figure A-2). The values for horizontal hydraulic conductivity ranged from 4.8×10^{-4} cm/s to 3.1×10^{-6} cm/s. One K_h value was determined for each site except

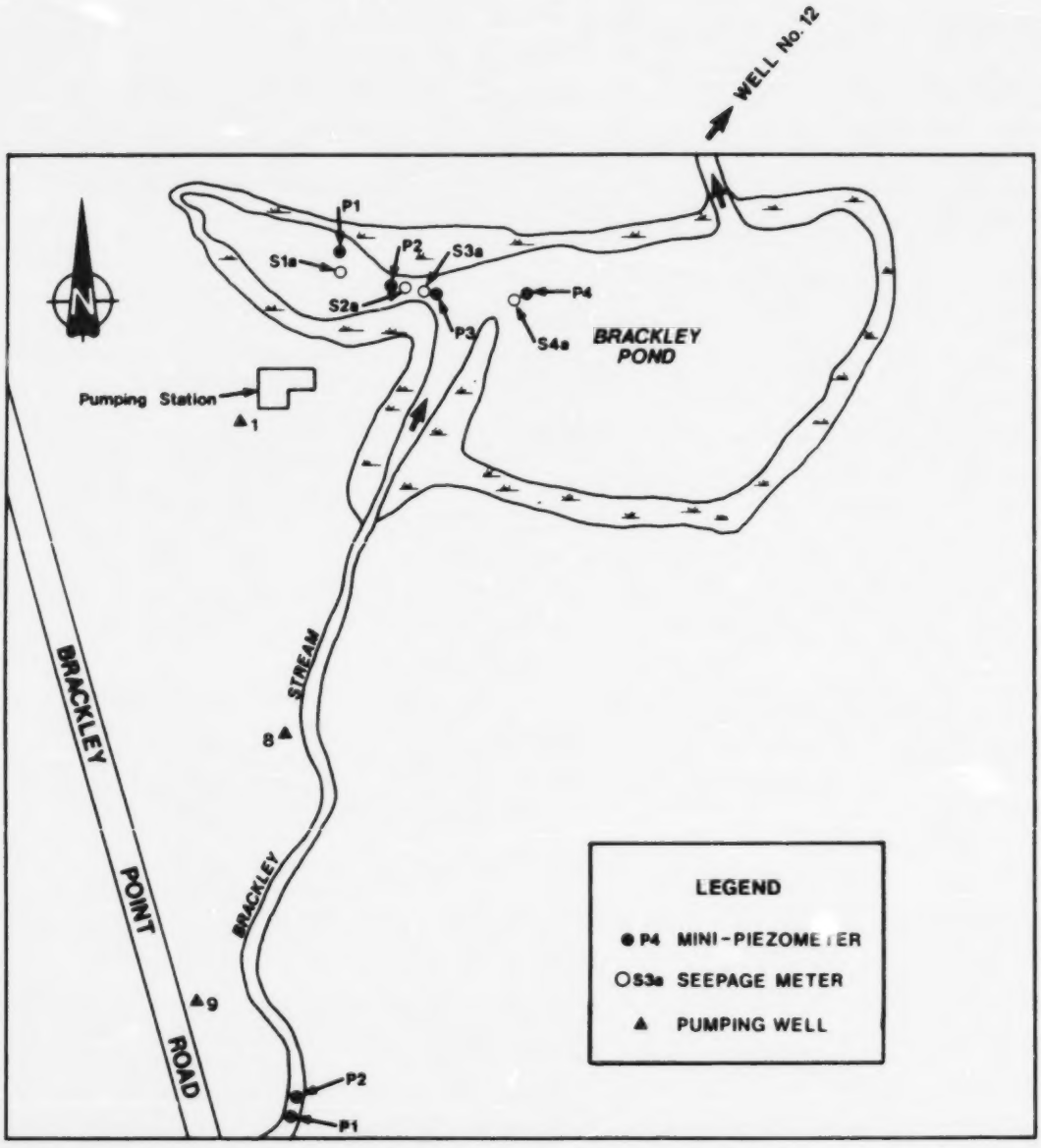

Figure A-1 Locations of Instrumented Sites at Brackley Stream and Brackley Pond.

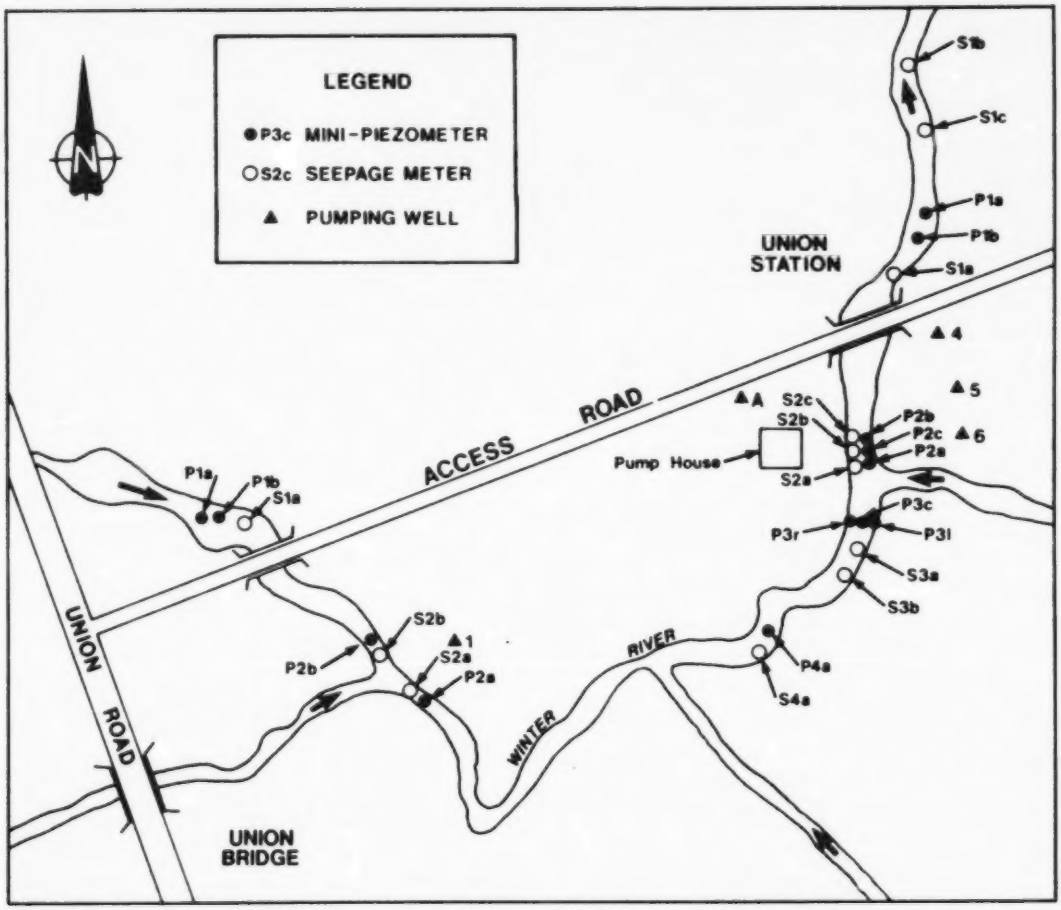

Figure A-2 Locations of Instrumented Sites at Union Bridge and Union Station.

1a and 2b where two measurements were made. Measured values at site 1a varied from the mean by 122%, while the variation between measured values at site 2b was 12%.

Seepage meter 1a was placed in silty sand and gravel, and was used to determine vertical hydraulic conductivities. Values ranged from 1.1×10^{-3} to 1.4×10^{-3} cm/s.

Seepage meter 1b was placed in silty pebbly sand. Field K_v values ranged from 4.8×10^{-3} to 2.2×10^{-4} cm/s. Field values of K_v from seepage meters 1a, 1b and 3a varied by 70, 86 and 49% respectively.

Hardy's Pond

One K_h value was measured in the mini-piezometers 1a, 1b, 1c, 1d and 2d in Hardy's Pond (Figure A-3), at respective depths of 109, 89, 58.5, 28 and 25 cemtimetres. Computed values of K_h ranged from 3.0×10^{-3} to 3.5×10^{-4} cm/s, and varied by 45% from the mean.

K_v measurements were determined from seepage meters b, c and d at Hardy's Pond (Figure A-3), which were placed in sand and gravel. Conductivity values ranged from 4.4×10^{-2} to 8.7×10^{-4} cm/s. The spread among values was 129.5%. Individual variations were b(53.1%), c(18.7%), and d(23.11%).

York Stream

A total of six K_h values were measured from mini-piezometers 1, 2 and 3 at York Stream (Figure A-4). No measurements were available for piezometer No. 4. Values varied by less than one order of magnitude and ranged between 2.7×10^{-4} and 7.1×10^{-5} cm/s. Respective depths were 1 (117 cm), 2 (86 cm), and 3 (64 cm). Measurement variation from the mean for all values was 59%.

K_v values were measured from seepage meters a and b in York Stream, which were placed in medium sand. Two K_v values were obtained from seepage meter 1a (4.9×10^{-3} cm/s and 4.0×10^{-3} cm/s), and seven from seepage meter b. All values ranged from 5.2×10^{-4} to 1.3×10^{-4} cm/s. Measured values from seepage meter a varied by 4% from the mean, and by 39% in seepage meter b.

York Pond

Four horizontal hydraulic conductivity values were measured at York Pond, two each from Mini-piezometer 1a and 1b (Figure A-4). Values for horizontal hydraulic conductivity at Site 1a were 1.9×10^{-3} and 6.6×10^{-3} cm/s. The horizontal hydraulic conductivities measured in mini-piezometer 1b were 2.6×10^{-3} and 5.2×10^{-4} cm/s. Mini-piezometer 1a was 102 cm deep, while mini-piezometer 1b was 56 cm deep. coefficients of variation were 55% and 33% from 1a and 1b respectively.

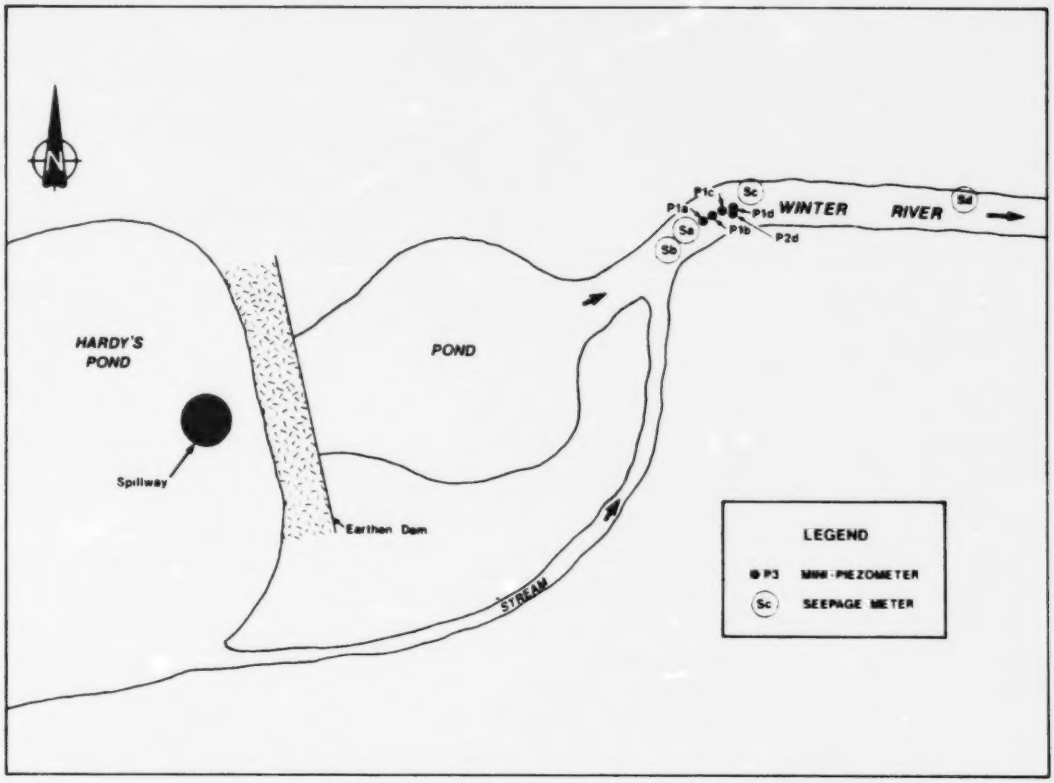

Figure A-3 Locations of Instrumented Sites at Hardy's Pond.

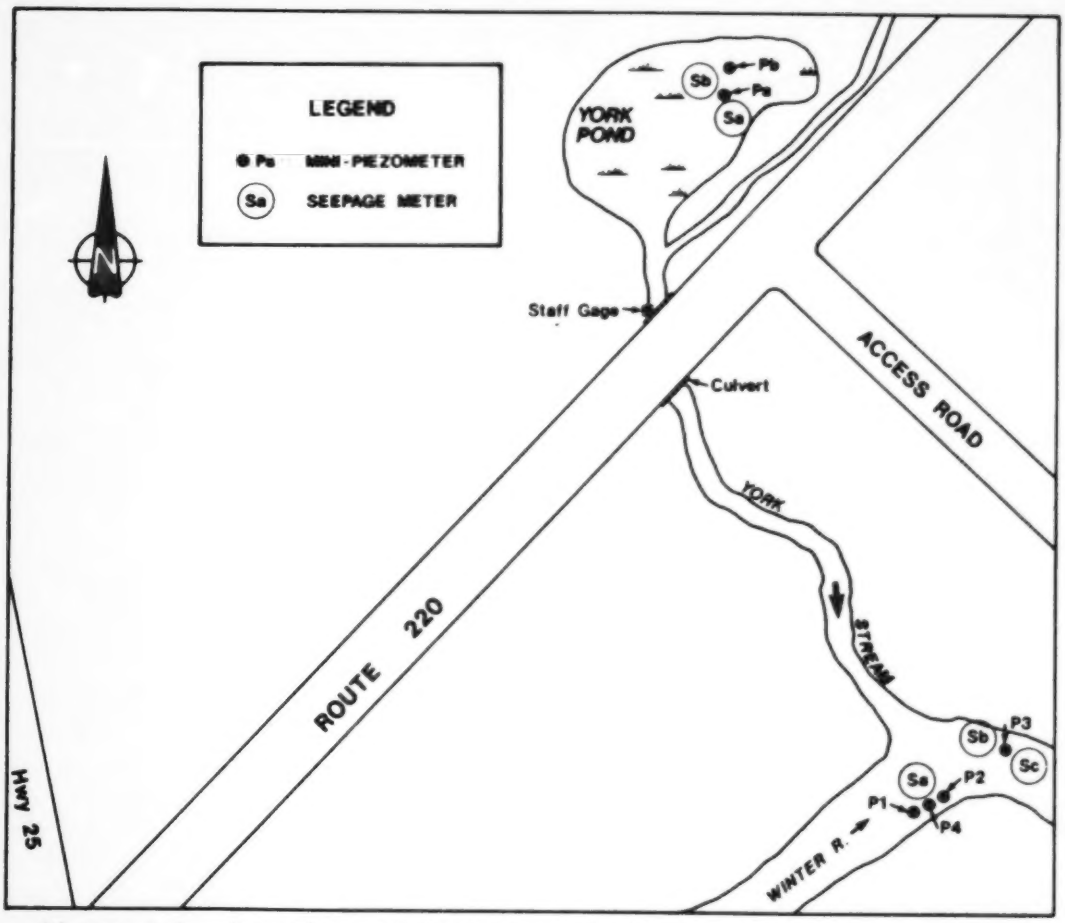

Figure A-4 Locations of Instrumented Sites at York Stream and York Pond.

Nine vertical hydraulic conductivity values were determined from seepage meters a and b at York Pond, the meters being set in sandy silt. Computed K_v values fell within an order of magnitude of each other, and ranged from 1.6×10^{-3} to 3.1×10^{-3} cm/s. The coefficient of variation for all values was 39%, with variations of 17% in seepage meter a and 63% in seepage meter b.

Officers Pond

Mini-piezometers 1a, 2a and 3a were used to determine four K_h values (Figure A-5), and were placed at depths of 56 cm, 60 cm and 31 cm respectively. Computed values of K_h varied by about one order of magnitude, and ranged from 3.5×10^{-4} to 3.2×10^{-5} cm/s. The coefficients of variation from two tests on piezometer 2a, and for K_h values from all piezometers, were 15% and 18% respectively.

K_v values were obtained from seepage meters a, b and c at Officers' Pond (Figure A-5). The meters were placed in clayey sandy silt. Values of K_v from eleven sample measurements ranged from 3.4×10^{-3} to 1.73×10^{-3} cm/s. Variations from the mean values in seepage meters a, b and c were 8%, 7% and 4% respectively.

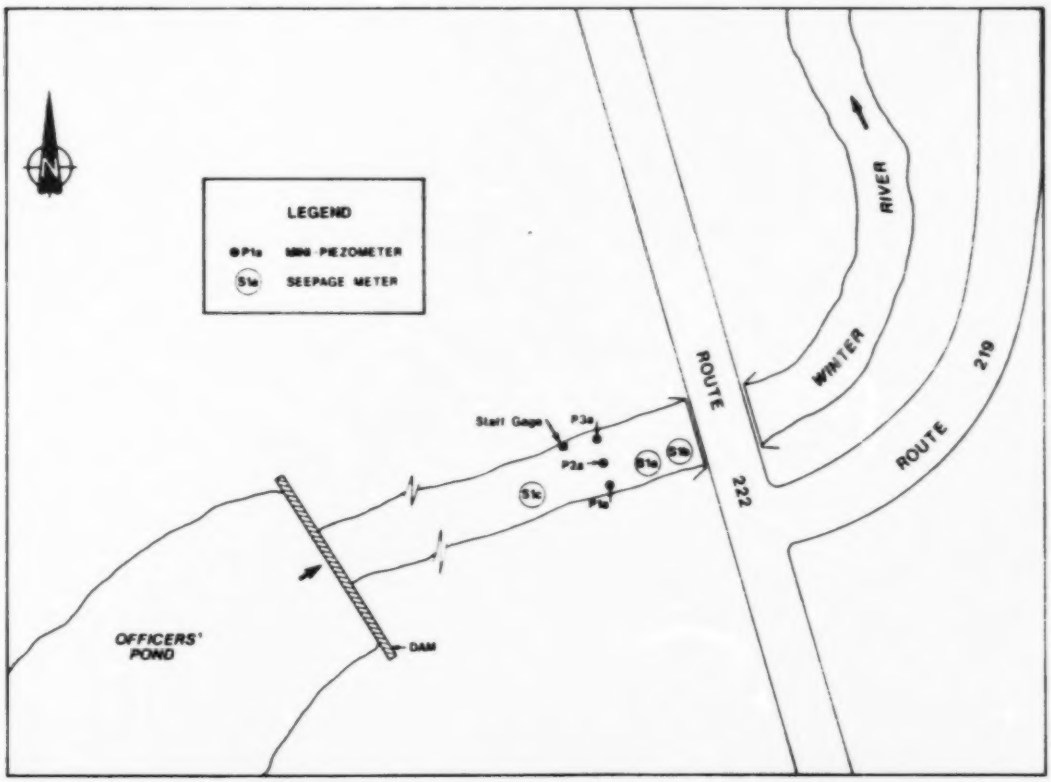

Figure A-5 Locations of Instrumented Sites at Officers' Pond.

Suffolk

A total of eleven K_h values were measured at Suffolk in mini-piezometers 1a, 1b, 2a, 2b, 3a and 3b (Figure A-6), and were placed at depths of 118, 51, 119, 64, 130 and 65 cemtimetres respectively. Measurements were completed twice in all mini-piezometers except 2a. Computed values of K_h ranged from 4.4×10^{-5} to 2.2×10^{-6} cm/s. Individual coefficients of variation were 1a (15%), 1b (3%), 2a (15%), 2b (13%), 3a (28%), and 3b (16%).

At Suffolk, a total of 20 K_v values were measured from seepage meters 1b, 2b, 2c and 3 (Figure A-6). Seepage meter 1a was placed in fine to medium sand, 2c and 2b were placed in pebbly gravel, and No. 3 in fine sand. Vertical conductivity values ranged from 6.0×10^{-3} to 5.0×10^{-4} cm/s. The coefficient of variation for all measurements was 21%.

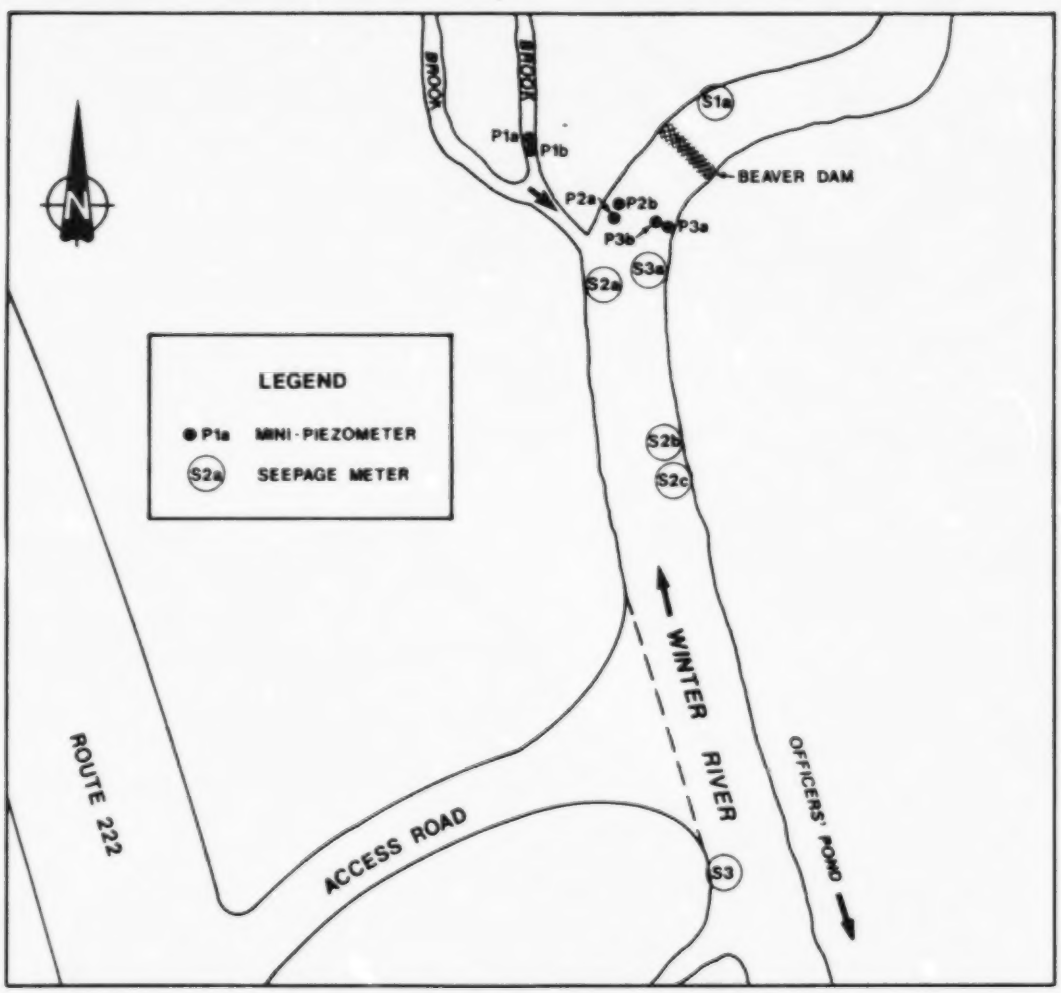

Figure A-6 Locations of Instrumented Sites at Suffolk.